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THE UNITED KINGDOM¹

David Edgerton and John V. Pickstone†

The territory of the United Kingdom of Great Britain and (Northern) Ireland, as it now is, has been the site of major scientific endeavours from the seventeenth century to the present, as is evident from any history of science. Indeed with the great expansion of Anglophone historiography of science since the 1970s, British cases, for the period 1750 to 1914 especially were central to general arguments about the nature of science, situated in very local contexts, but speaking to global concerns.² In contrast, national modes of writing long suggested systematic deficits in British science. In the 1820s, Charles Babbage reflected on the “decline of science” compared to Continental Europe, and later in the century scientific campaigns relied on exaggerated contrasts with other nations, especially

¹ Thanks to Sam Alberti, Peter Bowler, Sabine Clarke, Jonathan Harwood, Jeff Hughes, Greta Jones, Andrew Mendelsohn, Jack Morrell, Joan Mottram, Andrew Warwick, Duncan Wilson, and Michael Worboys for their comments and suggestions leading to the 2008 version of this paper. That paper was the subject of a workshop at the Centre for the History of Science, Technology and Medicine at King’s College London in June 2016 at which many useful comments were made. David Edgerton is grateful to John Pickstone’s family for permission to revise what is his last work for publication, and dedicates it to his memory. John Pickstone died in February 2014.

² For example, Bernard Lightman, ed., *Victorian Science in Context* (Chicago: University of Chicago Press, 2008). Evolution has been a central concern. See, for example, Robert M. Young, *Darwin’s Metaphor: Nature’s Place in Victorian Culture* (Cambridge: Cambridge University Press, 1985).

Germany.³ This history of retardation appears to some degree in J. D. Bernal's work of the 1930s, and very clearly in C. P. Snow's 1950s essay on *The Two Cultures* (much is a brief history of British science) as well as in many later reflections by scientists.⁴ Many academic historians of British science also echoed this analysis in work from the 1950s to the 1980s and indeed beyond.⁵ Indeed the deficit account of British science (with exceptions made for "pure" science) was a central element in the declinist national

³ Charles Babbage, *Reflections on the Decline of Science in England, and on Some of its Causes* (London: B. Fellowes, 1830); Graeme Gooday, "Lies, Damned Lies and Declinism: Lyon Playfair, the Paris 1867 Exhibition and the Contested Rhetorics of Scientific Education and Industrial Performance," in *The Golden Age. Essays in British Social and Economic History, 1850-70*, ed. Ian Inkster (London: Ashgate, 2000).

⁴ For the idea of "anti-histories" of British science see David Edgerton, *Warfare State: Britain 1920-1970* (Cambridge: Cambridge University Press, 2005), chap. 5.

⁵ J. D. Bernal, *The Social Function of Science* (London: Routledge and Kegan Paul, 1939); Donald S. L. Cardwell, *The Organisation of Science in England* (London: Heinemann, 1957); C. P. Snow, *The Two Cultures and the Scientific Revolution* (Cambridge: Cambridge University Press, 1959); J. G. Crowther, *Science and Modern Society* (London: Cresset, 1967); Hilary Rose and Steven Rose, *Science and Society* (Harmondsworth: Penguin, 1969); P. G. Werskey, *The Visible College: A Collective Biography of British Scientists and Socialists of 1930s* (London: Allen Lane, 1978, Free Association, 1988); Philip Gummett, *Scientists in Whitehall* (Manchester: Manchester University Press, 1980); F. Steward and David Wield, "Science, Planning and the State," in *State and Society in Contemporary Britain*, ed. G. McLennan *et al.* (Cambridge: Polity, 1984), pp. 176-203; Peter Alter, *The Reluctant Patron: Science and the State in Britain 1850-1920* (Oxford: Berg, 1987); Tom Wilkie, *British Science and Politics since 1945* (London: Blackwell, 1991). On engineers see Robert A. Buchanan, *The Engineers: A History of the Engineering Profession in Britain, 1750-1914* (London: Jessica Kingsley, 1989).

historiography of late nineteenth and twentieth century Britain.⁶ Thus British history and the history of British science were brought together in a way that marginalised science, as part of an argument for more science.

However, the nature of the historical arguments about science and the nation has shifted very significantly since the early 1990s, to one where the United Kingdom has been clearly one of the great scientific powers. It is the presence and significance of science for national and imperial history which is now stressed, in a new synthesis in which the strength of British science is used to explain many distinctive features of the United Kingdom. In this new narrative the declinist accounts have their place, not as true accounts to be used as sources, but as a historical peculiarity of interest. This chapter is a first attempt to provide general synthetic account of British science/science in British national and imperial history in the light of these fresh approaches. Its purpose is to guide students to arguments and literatures, and to help them avoid many common misunderstandings derived from the

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⁶ For declinist accounts see David Landes, *The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present* (Cambridge: Cambridge University Press, 1969); Keith Pavitt, ed., *Technical Innovation and British Economic Performance* (London: Macmillan, 1980); Correlli Barnett, *The Audit of War: The Illusion and Reality of Britain as a Great Nation* (London: Macmillan, 1986). For a review of the declinist literature, a definition, and alternatives see David Edgerton, "The Prophet Militant and Industrial: The Peculiarities of Correlli Barnett," in *Twentieth Century British History*, 2 (1991), 360-79; David Edgerton, *Science, Technology and the British Industrial 'Decline' 1870-1970* (Cambridge: Cambridge University Press, 1996); David Edgerton, "The Decline of Declinism," *Business History Review*, 71 (1997), 201-6; Jim Tomlinson, *The Politics of Decline. Understanding Post-war Britain* (Harlow: Longman, 2001).

older framings (which alas persist), and to help others towards richer visions of the intersections of scientific and national histories, and to sensible international comparisons.⁷ This account draws on particular ways of framing what we take to be science, one which stresses the *varieties* of knowledge and practice, their connections to institutions, and rejects the identification of science with research in selected academic disciplines – thus the attention given here to science in medicine and medical education, chemistry, engineering, mathematics, industry, and the military; the attention to research and non-research science, the importance of museums as well as laboratories, and so on.⁸ For reasons of space and practicality only intermittent attention is given to the social sciences, recognizing that this is an area of increasing interest.⁹ We are not setting out to describe

⁷ For recent powerful examples see David Bloor, *The Enigma of the Aerofoil: Rival Theories in Aerodynamics, 1909-1930* (Chicago: Chicago University Press, 2011), comparing UK and Germany; Chris Manias, *Race, Science, and the Nation: Reconstructing the Ancient Past in Britain, France and Germany* (London: Routledge, 2013); William Thomas, *Rational Action: The Sciences of Policy in Britain and America, 1940-1960* (Cambridge, Mass: MIT Press, 2015); Hermione Giffard, *Making Jet Engines in World War II: Britain, Germany, and the United States* (Chicago: University of Chicago Press, 2016).

⁸ For methods and exemplification see John V. Pickstone, *Ways of Knowing: A New History of Science, Technology and Medicine* (Chicago: Chicago University Press, 2001); John Pickstone, "Science in Nineteenth Century England: Plural Configurations and Singular Politics," in *The Organisation of Knowledge in Victorian Britain*, ed. M. Daunton (Oxford: Oxford University Press, for the British Academy, 2005), pp. 29-60; David Edgerton, "Time, Money, and History," *Isis*, 103 (2012), 316-27.

⁹ Some recent studies from historians/sociologists include Michael Savage, *Identities and Social Change in Britain since 1940: The Politics of Method* (Oxford: Oxford University Press, 2010); Peter Mandler, *Return from the Natives: How Margaret Mead Won the Second World War and Lost the Cold War* (London: Yale University Press, 2013); Erik Linstrum, *Ruling Minds: Psychology in the British Empire*

science in the United Kingdom in all its manifestations, but to emphasize particular forms that are especially significant/different in the British case. We will start not with the scientific or the industrial revolutions, or in the city, but in the countryside.

The British Enlightenment in Countryside and City

In an article on the peculiarities of the English, E. P. Thompson argued that the rationalisation and empiricism usually associated with the industrial revolution was first established in the countryside. In those newly enclosed landscapes, calculating tenant farmers and “improving” landlords saw that sheep might be “machines for turning grass into money.”¹⁰ Natural history, especially botany, was a common recreation of substantial land-owners and parsons, and of their wives and children.¹¹ They planted gardens, collected specimens, “improved” agriculture, and patronised the gentry, clergy, and professionals of the neighbouring county towns. They encouraged visiting lecturers and local medical charities and agricultural shows. It was part of a culture of collections and representations that included coins and prints, books and portraits, antiques and garden plants, as well as the creations of God. And the distinctions were fluid. Landscapes were created to look

(Cambridge, Mass.: Harvard University Press, 2016). Mathew Thomson, *Psychological Subjects: Identity, Culture, and Health in Twentieth-Century Britain Oxford* (Oxford: Oxford University Press, 2006),

¹⁰ E. P. Thompson, “The Peculiarities of the English,” (1965), reprinted in *The Poverty of Theory* (London: Merlin, 1978).

¹¹ David E. Allen, *The Naturalist in Britain: A Social History* (Princeton: Princeton University Press, 1994).

like pictures, and “pictured” through looking frames; prints were collected and inserted into dismembered books, or into scrap-books that could also contain pressed plants or pictures of animals. Plants could be classified, but so could portraits of English rulers, generals, and bishops.¹² Humans and their illnesses appeared in natural histories of man and in Hippocratic understanding of environments and disease.¹³ And since Britain was already a major colonial power, with great plantations in the Americas, British natural history was correspondingly global, as indeed it remained until the later twentieth century.¹⁴

This rural and aristocratic culture deeply affected the science of the metropolis. Aristocrats and high gentry often spent part of the year in London, where they could join special societies for botany, say, or antiquarianism. Thus in London, as also in Edinburgh and Dublin, the knowledges of the provinces were drawn together and reinforced with the metropolitan expertise of doctors, instrument makers, and lecturers. The Royal Society of London, dating from the seventeenth-century Restoration, was notably aristocratic and its *Proceedings* carried many reports of local phenomena. The Royal Society of Edinburgh

¹² Marcia Pointon, *Hanging the Head: Portraiture and Social Formation in Eighteenth-Century England* (New Haven: Yale University Press, 1993).

¹³ Roy Porter, *The Making of Geology: Earth Science in Britain, 1660-1815* (Cambridge: Cambridge University Press, 1977); L. J. Jordanova and Roy Porter, eds., *Images of the Earth: Essays in the History of the Environmental Sciences* (Chalfont St. Giles: British Society for the History of Science, 1979).

¹⁴ Robert Stafford, *Scientist of Empire: Sir Roderick Murchison, Scientific Exploration and Victorian Imperialism* (Cambridge: Cambridge University Press, 1989); Richard Drayton, *Nature's Government: Science, Imperial Britain, and the Improvement of the World* (New Haven: Yale University Press, 2000).

(founded in 1783) and the Royal Irish Academy in Dublin (1785)¹⁵ reflected the enlightenment cultural revivals in the home nations. Aristocratic philanthropists founded one of the key scientific arenas of scientific London, the Royal Institution, in 1799, to help better the conditions of the poor by improving agriculture and the sanitation of cities.¹⁶

The culture of improvement was far from just being aristocratic. In London, as in the new provincial centers of industry, educated gentry, clergy, and doctors might discuss schemes for manufactures, or for the better running of schools or charities – well illustrated by the Lunar Society (an informal dining club in the West Midlands), by the Manchester Literary and Philosophical Society, and by the new encyclopaedias and magazines that presented

¹⁵ For introductions to eighteenth century themes see G. S. Rousseau and Roy Porter, eds., *The Ferment of Knowledge: Studies in the Historiography of Eighteenth-Century Science* (Cambridge: Cambridge University Press, 1980); Roy Porter, *The Enlightenment* (Basingstoke: Palgrave, 2001); Roy Porter, ed, *The Cambridge Illustrated History of Medicine* (Cambridge: Cambridge University Press, 1996); Roy Porter, ed, *Cambridge History of Science*, vol. 4: *Eighteenth-Century Science* (Cambridge: Cambridge University Press, 2003).

¹⁶ Morris Berman, *Social Change and Scientific Organisation: The Royal Institution, 1799-1844* (London, Heinemann Educational, 1978).

“histories” of industry and of society, as well as of nature.¹⁷ Enlightenment knowledge was utilitarian as well as decorative, and analytical as well as natural-historical.¹⁸

In this account it may be noted that universities have been absent, perhaps unfairly. Indeed, Cambridge in particular had been reformed in the late eighteenth century with the introduction of written exams, and later the development of very intensive and large-scale pedagogical regimes based on mathematics.¹⁹ Scottish universities were especially significant in this period.²⁰ From the Act of Union in 1707, when Scotland lost its own parliament, civic leaders worried about the draining of wealth and influence from Edinburgh to London. To stem that tide, the “new town” was planned and Edinburgh University was regenerated on the model of Leiden, to attract students from England and the American colonies, and to educate Scottish students who might otherwise go abroad. Edinburgh was the chief university for the educated Dissenters of England, and its teachers

¹⁷ R. E. Schofield, *The Lunar Society of Birmingham: A Social History of Provincial Science and Industry in Eighteenth-century England* (Oxford: Clarendon Press, 1963); Ian Inkster, *The Social Context of an Educational Movement: a Revisionist Approach to the English Mechanics' Institutes, 1820-1850* (Oxford: Carfax Publishing, 1976).

¹⁸ Larry Stewart, *The Rise of Public Science: Rhetoric, Technology and Natural Philosophy* (Cambridge, Cambridge University Press, 1992); Roy Porter, *Enlightenment: Britain and the Creation of the Modern World* (London: Penguin, 2001).

¹⁹ Andrew Warwick, *Masters of Theory: A Pedagogical History of Mathematical Physics at Cambridge, 1760-1930* (Chicago: Chicago University Press, 2003).

²⁰ N. T. Philippson and Rosalind Mitchison, eds., *Scotland in the Age of Improvement: Essays in Scottish History in the Eighteenth Century* (Edinburgh: Edinburgh University Press, 1970).

a major reference point for formal and informal medical and scientific groupings in the industrialising provinces. Science was, of course, bourgeois too.

Politics: Repression and Resurgence

The Revolutionary and Napoleonic Wars might be seen as separating the characteristic cultural forms of the eighteenth-century from those of the nineteenth. As well as impacting very directly on the British Isles, fostering it is claimed a new notion of Britishness, the wars were of obvious political and ideological significance at home, with complex consequences for scientific knowledge. So as to avoid suppression, some of the nascent working class societies presented themselves as engaged with science rather than politics.²¹ Middle-class groupings, such as the Literary and Philosophical Societies, found it convenient to focus on chemistry or meteorology when their memberships were deeply divided over political and social questions.²² In Edinburgh, from the 1790s, the free-thinking enlightenment heroes came under attack from evangelicals eager to recruit a more traditional God to the defence of public order; the disputes over evolutionary theories were intense. The Geological Society of London, founded in 1807, tried to avoid religious

²¹ Paul Weindling, "Science and Sedition: How Effective were the Acts Licensing Lectures and Meetings, 1795-1819?," *British Journal for the History of Science*, 13 (1980), 139-53.

²² Arnold Thackray, "Natural Knowledge in Cultural Context: the Manchester Model," *American Historical Review*, 79 (1974), 672-709.

politics by focussing on the puzzles of the new stratigraphy.²³ Humphry Davy, a protégé of radical medical circles in Bristol, moved to the Royal Institution in London and became more conservative. He made spectacular use of one of the first public laboratories, becoming the main British actor in European debates about electricity and chemistry. He was also the patron of Michael Faraday, the humble-born philosopher of electricity, who proved exemplary both for self-help and for experimental physics.²⁴

Because intellectual commerce with France was disrupted until after Waterloo, the revolutionary changes in professional education and museums were little felt in Britain until the 1820s, when, for example, medical students began to visit Paris to complete their training. In mathematics, the 1820s saw the “analytical revolution,” which brought French mathematical and pedagogical methods to Britain, and especially to the great mathematical university of Cambridge. After the political crisis of Peterloo, when cavalry attacked a large crowd of protesters calling for parliamentary reform at St Peter’s Field, Manchester in 1819, the provincial middle-classes found their voice again, in part to speak of reforms that would head-off the growing threat of working-class disorder. And when the British “ancien regime” ended, symbolically, with the Reform Act of 1832, the new regime in

²³ Martin J. S. Rudwick, *The Great Devonian Controversy: The Shaping of Scientific Knowledge Among Gentlemanly Specialists* (Chicago: University of Chicago Press, 1985); Nicholas Rupke, *The Great Chain of History: William Buckland and the English School of Geology* (Oxford: Clarendon Press, 1983).

²⁴ Jan Golinski, *Science as Public Culture: Chemistry and Enlightenment in Britain* (Cambridge: Cambridge University Press, 1992); Frank A. J. L. James, ‘*The Common Purposes of Life*’: *Science and Society at the Royal Institution of Great Britain* (Aldershot: Ashgate, 2002).

London, and especially in the provinces, gave larger roles to merchants, industrialists, and professionals. Many such professionals and activists were keen cultivators of science. Indeed, while certain kinds of natural theology and natural philosophy could serve as a shield for conservatives, the “science” that spanned the new analytical disciplines was becoming a weapon for reformers and radicals alike.²⁵

Medical students and some of their teachers had a reputation for political radicalism, and their evolutionary theories encouraged politicised artisans to develop anti-clerical accounts of man.²⁶ In the more radical of the Mechanics’ Institutes from the 1820s, and in the socialist “Halls of Science” around 1840, evolutionary speculation mixed with versions of political economy that stressed property in skills as much as in capital, and with phrenological teachings that promised deep knowledge of character.²⁷ Though the working classes were sometimes allowed into middle-class museums, many workers with a taste for collecting and naming plants exercised their skills in public-houses, to the distress of their

²⁵ Richard Yeo, “William Whewell, Natural Theology and the Philosophy of Science in Mid Nineteenth-Century Britain,” *Annals of Science*, 36 (1979), 493-519; Richard Yeo, “William Whewell on the History of Science,” *Metascience*, 5 (1987), 25-40; John H. Brooke, *Science and Religion: Some Historical Perspectives* (Cambridge: Cambridge University Press, 1991). On science and reform the classic work is Jack Morrell and Arnold Thackray, *Gentlemen of Science: Early Years of the British Association for the Advancement of Science* (Oxford: Oxford University Press, 1981).

²⁶ Adrian Desmond, *The Politics of Evolution: Morphology, Medicine and Reform in Radical London* (Chicago: Chicago University Press, 1989).

²⁷ Roger Cooter, *The Cultural Meaning of Popular Science: Phrenology and the Organisation of Consent in Nineteenth-Century Britain* (Cambridge: Cambridge University Press, 1984).

would-be patrons who liked to draw a line between drink and self-improvement.²⁸ These plebian and radical contexts and doctrines have proved attractive to historians for political reasons as well as for the connection with Darwinism, but one should not underestimate the opposition – the mobilisation of science by Whigs and liberals, and indeed by conservatives. Most Mechanics’ Institutes were in fact run by middle-class paternalists, and their clients were often shop-keepers and clerks seeking advancement. To approximate the laws of liberal political economy to those of Newton lent the former a useful inscrutability; and phrenology, for many artisans as for its middle-class adherents, served to reinforce individualism.²⁹ And though comparative anatomy could be subversive of man’s special status, and the importation of continental medical sciences provided a niche for young doctors, the medical profession remained dominated by hospital consultants not noted for their intellectual or social concerns. Public health and “state-medicine” were indeed radical causes in the 1830s, but few doctors showed much interest until the 1850s.³⁰ Whig intellectuals held to middle roads, and from the 1820s they had a London base in what became University College (conservatives founded King’s College to bolster Anglican claims).

²⁸ Anne Secord, “Science in the Pub – Artisan Botanists in Early Nineteenth-Century Lancashire,” *History of Science*, 32 (1994), 269-315.

²⁹ Barry Barnes and Steve Shapin, *Natural Order: Studies of Scientific Culture* (London: Sage Publications, 1979).

³⁰ Christopher Hamlin, *Public Health and Social Justice in the Age of Chadwick; Britain, 1800-1954* (Cambridge: Cambridge University Press, 1998); Ivan Waddington, *The Medical Profession in the Industrial Revolution* (Dublin: Humanities Press, 1984).

The age of reform was important for science organisationally and institutionally at the national level. Geologists succeeded in establishing the (state) Geological Survey (1835).³¹ The Royal Society of London was reformed in 1847 to make it a professionally oriented learned society, and new national societies were formed, for example the Astronomical Society of London (1820) and the Chemical Society (1841). Engineers created the Institution of Civil Engineers (1818), which covered parliamentary work for transport schemes, and the Institution of Mechanical Engineers (1847), which was more provincial and industrial in orientation.³² The British Museum was developed as a base for taxonomy and comparative anatomy, a new Museum of Practical Geology was linked with the Geological Survey, and pathological museums became essential to medical schools -- whether private or in the teaching hospitals. And the provincial enthusiasts so gathered were recruited by metropolitan “gentlemen of science” into the new British Association for the Advancement of Science, a pressure group consolidated through annual meetings in different cities.³³ The same pattern of organisation, characteristic of liberal reform, was followed by what became the British Medical Association.³⁴ The leaders of the BAAS

³¹ James A. Secord, “The Geological Survey of Great Britain as a Research School, 1839-1855,” *History of Science*, 24 (1986), 223-75.

³² Buchanan, *The Engineers*; Robert Bud and G. K. Roberts, *Science versus Practice: Chemistry in Victorian Britain* (Manchester: Manchester University Press, 1984); Colin Divall and Sean F. Johnston, *Scaling Up: The Institution of Chemical Engineers and the Rise of a New Profession* (Dordrecht, Boston and London: Kluwer Academic, 2000).

³³ Morrell and Thackray, *Gentlemen of Science*; Rudwick, *The Great Devonian Controversy*.

³⁴ Peter Bartrip. *Themselves Writ Large: The British Medical Association, 1832-1966* (London: BMJ Publishing Group, 1996).

mostly held paid posts in the universities; the “British Ass” linked them with the occasional lecturers, periodical writers, and with the enthusiasts for natural history, astronomy, microscopy or photography who generally met in local scientific societies, and who helped constitute the common context of middle-class thought.³⁵ It is notable though that we have a shift, from societies attached to place, like the Royal Society of London to organisations going by national names, such as the *British Association for the Advancement of Science*, an institution which met once a year in different cities. As the British world expanded, from 1884 it held the occasional meeting outside the United Kingdom, visiting Canada in 1884 and 1909, South Africa in 1905 and Australia in 1914.

As these examples indicate we are concerned largely with non-state, voluntary activity. Indeed what is striking is the extent to which this, and private commercial activity connected to science flourished. Commercial and educational museums were set up, often in the hope of popularising technology and encouraging invention.³⁶ Not least in great new industrial cities, local societies for science flourished. Manchester, for example, alongside its Literary and Philosophical Society (1781), sprouted societies (and museums) for natural history, geology, technology, and phrenology, quite independent of the state.

³⁵ James Secord, *Victorian Sensation: The Extraordinary Publication, Reception and Secret Authorship of Vestiges of the Natural History of Creation* (Chicago: University of Chicago Press, 2000).

³⁶ Iwan Rhys Morus, *Frankenstein's Children: Electricity, Exhibition, and Experiment in Early-Nineteenth-Century London* (Princeton: Princeton University Press, 1998).

Industry and Analysis

In the early to mid-nineteenth century the United Kingdom of Great Britain and Ireland (as it then was) was distinctive in its urbanisation and its industrialisation. Accounts of the industrial revolution written in the decades after the Second World War tended to focus on the possible inputs of science to industrialisation, and on the origins of the technical universities and technical institutions.³⁷ Later historians have stressed the many different roles of technical knowledges, latent as well as patent. They have looked less to industry than to civil engineering, government regulation, military and naval forces, medical professionalization, and the social roles of the sciences for middle or working-class groupings.³⁸ It has been hard to find science merely applied in industry, except in the chemical trades, but one might argue more widely -- for common attitudes demonstrated in both knowledge-seeking and money-making. For example, the inventions of textile machines by Lancashire artisans might be linked with their contemporary fondness for mathematics and botany as the (short-lived) prosperity of domestic hand-loom weavers encouraged a culture of self-instruction and an appreciation of “novelties.” Or, at the level

³⁷ A. E. Musson and E. Robinson, *Science and Technology in the Industrial Revolution* (Manchester: Manchester University Press, 1969); Donald S. L. Cardwell, ed., *Artisan to Graduate: Essays to Commemorate the Foundation in 1824 of the Manchester Mechanics' Institution, Now in 1974 the University of Manchester Institute of Science and Technology* (Manchester: Manchester University Press, 1974). This tradition has been revived in Joel Mokyr, *The Enlightened Economy: Britain and the Industrial Revolution, 1700-1850* (London: Penguin, 2011).

³⁸ See Margaret C. Jacob, *Scientific Culture and the Making of the Industrial West* (Oxford: Oxford University Press, 1997); Golinski, *Science as Public Culture*; Stewart, *The Rise of Public Science*.

of the urban professionals by the 1820s, we can see chemists, engineers, industrialists, and doctors trying to analyse into components of chemical matter, mechanical motions, industrial processes, or industrial society, so as to better understand the structures and dynamics across the range of the new sciences. Their analytical methodologies and ideologies helped link the rationalisation of industrial production with the political economy of Ricardo and with new analyses of the natural world then being produced by emergent “scientists.”³⁹

Indeed, the first half of the century, in the United Kingdom, as in France, was notable for analytical sciences and practices based on “elements” that were specific to each of these newly constituted disciplines. Lavoisier’s new system of chemical elements was the paradigm, but geology, botany, zoology, general anatomy, and engineering all had their elements (for example, strata, tissues, and elementary machines) from which bodies of various kinds were seen as compounded.⁴⁰ In the spaces between natural philosophy, chemistry, and engineering, new physical disciplines were created around the elements of heat, light, and the various kinds of electricity. As John Herschel noted in the most popular guide to scientific method: “In pursuing the analysis of any phenomenon, the moment we find ourselves stopped by one of which we perceive no further analysis...the study of that

³⁹ Pickstone, *Ways of Knowing*, pp. 83-102. The links between political economy and science have been a theme of the literature on, for example, Babbage and Kelvin. See also Margaret Schabas, *A World Ruled by Number: William Stanley Jevons and the Rise of Mathematical Economics* (Princeton: Princeton University Press, 1990).

⁴⁰ See Pickstone, *Ways of Knowing*.

phenomenon and of its laws becomes a separate branch of science.”⁴¹ It is no accident that in Britain as in France, there was much contemporary interest in the classification of the sciences, or that traditionalist natural philosophers such as William Whewell regarded the new disciplines as too unstable to serve as the basis for a scientific education, which should continue to be grounded in mathematical natural philosophy.⁴² For all these new subjects, especially in those fields close to agriculture and industry, for example stratigraphy, chemistry, work/energy, and political economy, British analysts were much more than copyists. Whig reformers (and some Tories and Radicals) ranged across these nascent disciplines and built them into political arguments. Charles Babbage, who had helped introduce French mathematics to Cambridge, also argued for the division and mechanisation of mathematical labor; he philosophised about industrial work as he lamented the lack of support for science in Britain.⁴³ The physician James Kay (-Shuttleworth) analysed the social body of Manchester, guided by the physiology he had learned at Edinburgh and the political economy of Ricardo; he moved to become a Poor Law Commissioner under Edwin Chadwick and then the first central administrator of

⁴¹ John Herschel, *Preliminary Discourse on the Study of Natural Philosophy* (London: Longman, 1830).

⁴² Menachem Fisch and Simon Schaffer, eds., *William Whewell, A Composite Portrait* (Oxford: Clarendon Press, 1991).

⁴³ Simon Schaffer, "Babbage's Intelligence: Calculating Engines and the Factory System," *Critical Inquiry*, 21 (1994), 201-28; William Ashworth, "Memory, Efficiency and Symbolic Analysis: Charles Babbage, John Herschel and the Industrial Mind," *Isis*, 87 (1996), 629-53; Martin Campbell-Kelly, ed., *The Works of Charles Babbage* (London: Pickering, 1989).

English education.⁴⁴ His Manchester contemporary, the devotee James Prescott Joule, applied himself to natural philosophy. A student of John Dalton and a son of a brewing family, Joule was sceptical of the 1830s enthusiasm for electrical machines, so he *measured* their efficiency, as practical engineers had learnt to assess that of steam engines. From these results he went on to conceptualise and measure the mechanical equivalent of heat, and so, via William Thomson's Cambridge mathematics and Glasgow engineering, laid one route to the principles of thermodynamics.⁴⁵

Fiscal-military State

If our account is unfamiliar in starting with the land before going on to more familiar industry, it is also unusual in looking at the armed services. Great Britain was, in a celebrated historiographical intervention, a “fiscal-military state.”⁴⁶ It had armed services operating across the world from the eighteenth century, at the center of which was the Royal Navy, a vast force backed up by industrial installations and educational and technical institutions barely known in the civilian world. Perhaps the most famous institution was the Royal Observatory at Greenwich, under the Astronomer Royal, and all under the

⁴⁴ John V. Pickstone, “Ferriar's Fever to Kay's Cholera: Disease and Social Structure in Cottonopolis,” *History of Science*, 22 (1984), 401-19; Mary Poovey, *Making a Social Body: British Cultural Formation, 1830-1864* (Chicago: University of Chicago Press, 1995).

⁴⁵ Donald S. L. Cardwell, *James Joule: A Biography* (Manchester: Manchester University Press, 1989); Crosbie Smith and M. Norton Wise, *Energy and Empire: A Biographical Study of Lord Kelvin* (Cambridge: Cambridge University Press, 1989).

⁴⁶ On science and the fiscal side see William Ashworth, *Customs and Excise: Trade, Production and Consumption in England, 1640-1845* (Oxford: Oxford University Press, 2003).

Admiralty, the navy ministry.⁴⁷ The Navy engaged and transported the great naturalists of the age around the globe, from Sir Joseph Banks, the great panjandrum of British science and for decades president of the Royal Society, to Charles Darwin, who sailed on the warship HMS *Beagle*, built at Woolwich Dockyard, and commanded by Robert Fitzroy RN, an aristocratic career naval officer and meteorologist, who would go on to create the Meteorological Office.⁴⁸ The army too had its great institutions like the Royal Military College (at Sandhurst from 1802), for infantry and cavalry, and the older Royal Military Academy, at Woolwich, for engineers and artillery officers. The latter had professors of mathematics, and indeed of chemistry, including Michael Faraday. The Royal Society of London was full of men from the armed forces, like Sir Francis Beaufort of the Navy, Sir Edward Sabine of the artillery (and later President of the Royal Society), Sir George Everest, and many others including medical officers of the armed services. They accounted for around 10 percent of the fellowship through the nineteenth century.⁴⁹ These institutions carried out great projects, including massive geodesic projects and great feats of precision measurement, from the Great Trigonometrical Survey of India (1802-1871), to the establishment of the precise distance between the Observatories of London and Paris,

⁴⁷ Richard Dunn and Rebekah Higgitt, *Finding Longitude* (London: Collins, 2014); Sophie Waring, "The Board of Longitude and the Funding of Scientific Work: Negotiating Authority and Expertise in the Early Nineteenth Century," *Journal for Maritime Research*, 16 (2014), 55-71.

⁴⁸ Michael S. Reidy, *Tides of History: Ocean Science and Her Majesty's Navy* (Chicago: University of Chicago Press, 2008).

⁴⁹ Thomas David, "British Scientists and Soldiers in the First World War (with special reference to ballistics and chemical warfare)," (PhD thesis, Imperial College, 2009)

making a universal time a reality.⁵⁰ Yet it is important to note that in the later nineteenth century, the state and armed forces loomed much less significantly in Britain than elsewhere. Thus the British military academies had nothing like the status or impact of the Ecole Polytechnique in France or the West Point Military Academy in the United States; indeed, state civil engineering colleges barely existed in the United Kingdom. From the mid-nineteenth century science and scientific education was principally a matter for higher civil society rather than state institutions and officials. State corps of military engineers, even naval architects, did not have anything like the same significance as they did in much of continental Europe. This is not to say that the state did not have specialist technical officers. The latter category included various kinds of public health doctor, chemists involved in the Alkali Inspectorate, inspectors of education (for example Matthew Arnold) or of Fisheries (a post T. H. Huxley once held).⁵¹

Religion and Education in Liberal Britain

Another important differentiating and complicating factor was religion. The United Kingdom was a Protestant nation – Catholics were “emancipated” only in 1829; and its established Protestant churches vied with Dissenting churches of many stripes. This was

⁵⁰ Michael Kershaw, “‘A thorn in the side of European geodesy’: Measuring Paris–Greenwich Longitude by Electric Telegraph,” *The British Journal for the History of Science*, 47 (2014), 637–60; Rebekah Higgitt, “A British National Observatory: The Building of the New Physical Observatory at Greenwich, 1889–1898,” *The British Journal for the History of Science*, 47 (2014), 609–35.

⁵¹ Oliver MacDonagh, *Early Victorian Government* (London: Weidenfeld and Nicolson, 1977)

the context of characteristic science-religion discussions. Such debates were echoed in the United States, but differed significantly from Continental patterns, which more clearly pitted atheists and agnostics against Catholicism.⁵² In the United Kingdom science and religions went together, though in varied forms. Darwin was buried in Westminster Abbey in 1882.⁵³ The educational institutions in which science flourished were mostly denominational; indeed, to be non-denominational much before mid-century was in effect a sectarian position. The key Anglican institutions were Oxford, Cambridge, and Trinity College, Dublin. These and other protestant universities emerged as great centers of scientific and mathematical learning. It is notable that most of the great Irish-born scientists – including Lord Kelvin, George Stokes, John Tyndall, Joseph Larmor, George Francis Fitzgerald, George Johnstone Stoney, and John Joly – were Protestants.⁵⁴ The Scottish Universities and the emergent London University were open to all faiths and more

Commented [HS2]: Full names

⁵² Secord, *Victorian Sensation*; Brooke, *Science and Religion*; Ian G. Barbour, *Issues in Science and Religion* (New York: Harper and Row, 1966). And see also Adrian Desmond and James Moore, *Darwin* (London: Penguin, 1991); Adrian Desmond, *Huxley: The Devil's Disciple* (London: Michael Joseph, 1994); Adrian Desmond, *Huxley: Evolution's High Priest* (London: Michael Joseph, 1997). Peter J. Bowler, *Reconciling Science and Religion: the Debate in Early Twentieth-century Britain* (Chicago: Chicago University Press, 2001) shows how the Victorian issues played out in a new age.

⁵³ For the consequences see James Moore, *The Darwin Legend* (London: Baker, 1994).

⁵⁴ Andrew Warwick, "The Sturdy Protestants of Science: Larmor, Trouton and the Motion of the Earth Through the Ether," in *Scientific Practice: Theories and Stories of Doing Physics*, ed. Jed Z. Buchwald and Greta Jones (Chicago: University of Chicago Press, 1995); Greta Jones, "Scientists against Home Rule," in *Defenders of the Union: A Survey of British and Irish Unionism*, ed. D. George Boyce and Alan O' Day (London: Routledge, 2001), pp. 188-208.

open to the new sciences. So too were the Queen's Colleges of the 1840s in Cork, Galway, and Belfast, but the Irish Catholic hierarchy banned their flocks from them, leaving Irish science almost wholly Protestant. When we look to T. H. Huxley and his co-conspirators in the X-Club, a small group of like-minded naturalists formed in 1864m we see how an emergent scientific community lobbied for influence, power, and the provision of new colleges that could accommodate their protégés.⁵⁵ Their message still has radical resonance – science, as a method, embodied the spirit of practical criticism, it questioned all tradition, including religion; it was the way of the future.⁵⁶

Commented [HS3]: Brief identification.

From the mid-nineteenth century there was a notable development in formal education, mostly private. The growth of formal medical education, in the hospital schools of London as in the proprietary medical colleges of the provinces, gave partial livings to teachers of chemistry, natural philosophy, and botany, as well as of the new medical sciences.⁵⁷ And from the 1840s, in London, medical students could also attend a new kind of college for scientific professionals: at the Royal College of Chemistry, A. W. von Hofmann brought to Britain the practical education in chemistry (and pharmacy) pioneered by Justus von

⁵⁵ Desmond, *Huxley: The Devil's Disciple*; Desmond, *Huxley: Evolution's High Priest*; Roy M. MacLeod, "The X Club: A Social Network of Science in Late-Victorian England," *Notes and Records of the Royal Society*, 24 (1970), 305-22.

⁵⁶ Pickstone, "Science in Nineteenth-Century Britain."

⁵⁷ William H. Brock, *The Fontana History of Chemistry* (London: Fontana Press, 1992); Roger French and Andrew Wear, eds., *British Medicine in an Age of Reform* (London: Routledge, 1991); Irvine Loudon, *Medical Care and the General Practitioner 1750-1850* (Oxford: Clarendon Press, 1986).

Liebig at the University of Giessen.⁵⁸ The College failed as a private venture, becoming part of the complex of scientific institutions supported from mid-century by the state and mostly collected into South Kensington, which, for all its debts to (the German) Prince Albert, was in many ways the *French* aspect of British science, a set of national educational museums and technical schools.

From mid-century, pressures mounted to reform the ancient universities. Reformers inside the universities hoped to benefit their disciplines by professionalising academic life and promoting research, as in Germany. Many of the external reformers were provincial Dissenters, keen to open up the ancient English universities for the next generation. Similar campaigns were mounted for the reform of the élite boarding schools – for the better moral-discipline of young English gentlemen and to maintain the intellectual legitimations of that social class against the claims to new knowledge evident in the northern cities and the technical professions.⁵⁹

In the northern cities, the higher education institutes most characteristic of the early century had been denominational colleges for clergy of various Dissenting kinds. From mid-century, secular colleges were founded, some of them (for example, in Manchester, and

⁵⁸ William H. Brock, *Justus von Liebig: The Chemical Gatekeeper* (Cambridge: Cambridge University Press, 1997); Jack Morrell, "The Chemist Breeders: The Research Schools of Liebig and Thomas Thomson," *Ambix*, 19 (1972), 1-46.

⁵⁹ For attitudes to science and the public schools, see Brian Simon, *The Two Nations and Educational Structure, 1780-1870* (London: Lawrence and Wishart, 1974), 299-318.

later Liverpool) with traditional curricula that contained arts subjects as well as sciences. Some, like Sheffield and Birmingham, concentrated on the sciences that were to benefit local industries. Some came close to failure, but by about 1870 they were thriving. Leading local industrialists were supporting academic entrepreneurs in developing science laboratories, especially for chemistry; and proprietary medical schools were amalgamating with the colleges, in part to secure the pre-clinical science teaching that medical educationists had managed to make compulsory under the 1858 Medical Act. Generally, the colleges benefited from the growth of a “diploma culture” -- the University of London acting as a national examination board.⁶⁰

Most professional scientists around mid-century curated *museums* or analyzed specimens for knowledge, diagnoses, or profit; they also lectured to large classes and performed demonstrations. Even T. H. Huxley, the Moses of experimental biology in Britain, did his own taxonomic and analytical biology in museums or in the field; and though many younger scientists owed their positions to him, he had no direct research descendants such as they would later boast. The growth of higher education in mid-century boosted the *museum sciences*. Thus the first major scientific institution in Oxford was the University Museum (of Natural History, with chemistry added on) promoted by Ruskin and opened in 1861. In London, the Royal School of Mines was associated with the Museum of Practical Geology; and when T. H. Huxley built the Normal School of Science in South Kensington to educate science teachers, it too contained a museum. In the 1870s the

⁶⁰ French and Wear, *British Medicine in an Age of Reform*; Loudon, *Medical Care and the General Practitioner*.

Natural History collections of the British Museum were moved to a splendid new Gothic cathedral of science in South Kensington; and from about the same date, throughout the country, municipal governments were developing public museums, often incorporating collections that had been assembled by local natural history societies and were used by the new civic colleges.⁶¹

Yet even as museums gained huge public audiences, they began to be marginalised in the academies, where from the 1860s professors of physical sciences concentrated on developing laboratories. These were first intended for the instruction of students, but some later housed organised research by advanced students and staff. Chemistry had led the way with the teaching laboratories of Thomas Thomson in Glasgow, and Hofmann in London. And when Owens College, Manchester raised money for extension and moved to its present site in the early 1870s, about half the space in the new building was devoted to Henry Roscoe's chemical institute – as large as anything in Germany and closely linked with local industry via consultancies and the provision of graduates.⁶² Physics followed. Glasgow boasted a physics laboratory created by William Thomson to give practical training to large numbers of students, while also serving his industrial connections,

⁶¹ Carla Yanni, *Nature's Museums: Victorian Science and the Architecture of Display* (London: Athlone Press, 1999).

⁶² Robert Kargon, *Science in Victorian Manchester: Enterprise and Expertise* (Manchester: Manchester University Press, 1977); for Manchester physics also see Peter J. Davies, "Sir Arthur Schuster, 1851-1934," (PhD thesis, University of Manchester (UMIST), 1983).

especially for telegraphy, which demanded laboratory testing and skilled technicians.⁶³ Indeed historians have fruitfully explored the connections of electrical telegraphy – particularly submarine telegraphy – with the emergent British physics and electro-magnetic theory.⁶⁴

The Cambridge pattern was interestingly different from that of London and the industrial provinces, with less stress on chemistry. It was not only important but huge relatively speaking: in mid-century some 100 students graduated in mathematics from Cambridge each year. Though most of these graduates went on to non-mathematical careers, Kelvin, James Clerk Maxwell, Stokes, and many other luminaries of science were numbered amongst the products: Cambridge *mathematicians* represent one of the main British contributions to nineteenth-century science.⁶⁵ The Cavendish laboratory was funded by the Duke of Devonshire (family name Cavendish), who was also a mathematician, an industrialist, and a statesman for science, and who, in the early 1870s, chaired a massive

⁶³ Smith and Wise, *Energy and Empire*; Robert Fox and Anna Guagnini, *Laboratories, Workshops and Sites: Concepts and Practices of Research in Industrial Europe, 1800-1914* (Berkeley: University of California Press, 1999); Graeme Gooday, "Precision Movement and the Genesis of Physics Teaching Laboratories in Victorian Britain," *British Journal for the History of Science*, 23 (1990), 25-51.

⁶⁴ For examples, see Simon Schaffer, "Late Victorian Metrology and its Instrumentation: A Manufactory of Ohms," in *Invisible Connections: Instruments, Institutions, and Science*, ed. Robert Bud and S. E. Cozzens (Bellingham, Wash.: SPIE Optical Engineering Press, 1992), pp. 23-56; Bruce Hunt, "Michael Faraday, Cable Telegraphy and the Rise of Field Theory," *History of Technology*, 13 (1991), 1-19.

⁶⁵ Andrew Warwick, *Masters of Theory: A Pedagogical History of Mathematical Physics at Cambridge, 1760-1930* (Chicago: Chicago University Press, 2003).

enquiry into the state of British science, an indication that the scientific resources of the nation had become an important issue. Its many recommendations largely went unfunded, but the institution he gave to Cambridge, sometimes then called a museum for physical science, proved crucial in diverting some of Cambridge's mathematical prowess towards experimentalism. The Cavendish failed to take off as a teaching laboratory until the mid eighties but became a center for analytical work on electrical standards, closely related to the telegraph industry. From the 1890s it was a major experimentalist laboratory with a program of research around cathode ray tubes, led by J. J. Thomson.⁶⁶ From 1895, when Cambridge laboratories were opened to graduates from elsewhere, they proved attractive to colonial scholarship boys as well as to rich Britons.⁶⁷ Another hugely productive Cambridge laboratory was the Cambridge physiological laboratory, dating also from the 1870s.

⁶⁶ On the Cavendish see Schaffer, "Late Victorian Metrology"; Simon Schaffer, "Accurate Measurement is an English Science," in *The Values of Precision*, ed., M. Norton Wise (Princeton: Princeton University Press, 1995); Jeffrey Hughes, "The Radioactivists: Community, Controversy and the Rise of Nuclear Physics" (PhD thesis, University of Cambridge, 1993); Andrew Warwick and Jed Z. Buchwald, ed., *Histories of the Electron: The Birth of Microphysics* (Cambridge, Mass.: MIT Press, 2001); Dong Won Kim, *Leadership and Creativity. A History of the Cavendish Laboratory, 1870-1919* (Dordrecht: Kluwer, 2002).

⁶⁷ On physiology, see Gerald Geison, *Michael Foster and the Cambridge School of Physiology* (Princeton: Princeton University Press, 1978); on Cambridge medicine more generally, see Mark Weatherall, *Gentlemen, Scientists, and Doctors: Medicine at Cambridge, 1800-1940* (Rochester, N.Y.: Boydell Press in association with Cambridge University Library, 2001).

By about 1890, “endowment of research” featured in funding campaigns for universities, and schools of advanced students working under key researchers were the norm in most disciplines by about 1900. But, like the endowment of universities for teaching, and quite unlike the German model, the endowment of research laboratories in British universities was largely a matter of private philanthropy.⁶⁸ So too was the provision of new teaching hospitals that sometimes accompanied the new universities, and which emphasized research and education as well as care. Medical research, especially around bacteriology, became a favored object for philanthropy, in hospitals, universities, and a few independent institutions.⁶⁹ As in the United States from the same period, crucial large donations often came from the fortunes of industrialist and merchants -- for example, the legacy of Joseph Whitworth, the Manchester engineer, which helped provide a new technical college and a teaching hospital, as well as an art gallery and scholarships for would-be engineers.

By the end of the nineteenth century science in the United Kingdom could be characterised as essentially a private rather than a state activity, but something which was nevertheless

⁶⁸ On universities generally see Keith Vernon, *Universities and the State in England, 1850-1939* (London: Routledge, 2004); Mark Pendleton, “‘A Place of Teaching and Research’: University College London and the Origins of the Research University in Britain, 1890-1914” (PhD thesis, University of London, 2001); and see June Jones, “Science, Utility and the ‘Second City of the Empire’: the Sciences and Especially the Medical Sciences at Liverpool University, 1881-1925” (PhD thesis, University of Manchester (UMIST), 1989).

⁶⁹ See for example, Michael Worboys, *Spreading Germs. Disease Theories and Medical Practice in Britain, 1856-1900* (Cambridge: Cambridge University Press, 2000); Rosemary Wall, *Bacteria in Britain, 1880-1939* (London: Routledge, 2015).

of national concern. As Lyell, Darwin, and Joule resoundingly showed, men of independent means or commercial employment conducted scientific research work of major importance. In London by the later nineteenth century, science was a matter of interconnecting networks of educationalists, consultants, businessmen, and researchers.⁷⁰ And while science as an activity might be called more professional (though the term needs to be used with great caution) it was also in some sense more concentrated in particular institutions, which were now very clearly institutions of larger scale than before, much more urban, and much more connected to industry than in the eighteenth or early nineteenth centuries. And though not all scientists (a word one can begin to use, though man of science was a much more common designation) were not all liberals, in some larger sense science and liberalism marched together. A small state, as the British state had become, played a relatively much smaller role in the sciences than on the Continent, a source of pride to many of its great luminaries.

Education, Industry, and Empire (1890-1914)

The years around 1900 saw a rapidly expanding provision for higher scientific and technical education. Campaigners tended to ignore the existing, very varied provision for education, and its rapid development, in a variety of forms, and typically supported by philanthropy. The general increase in the quality of scientific and technical education was evidenced by the disappearance from British firms of foreign and foreign-trained scientists

⁷⁰ See for example, Hannah Gay, "East End, West End: Science, Culture and Class in Mid-Victorian London," *Canadian Journal of History*, 32 (1997), 153-83.

and engineers. A crude estimate would suggest that the number of annual graduates in science and engineering increased fourfold in twenty years.⁷¹ But in some cases there was an explicit rejection of the German model of provision, and comparisons with continental countries need to be carefully made. For example, whilst on the continent most universities, higher technical schools, and medical schools were wholly owned by the state (in Germany not the Reich but the state governments), this was rarely the case in Britain, where the universities were mostly charitable corporations. The exceptions were the new technical colleges owned by the major cities and towns, plus the rather special case of the Royal College of Science, which incorporated the Royal School of Mines, together with the private City and Guilds College, and was later transferred (1907) from the ownership of the Board of Education to the new Imperial College of Science and Technology. Ireland too had a state-run Royal College of Science in Dublin, in a building later taken over by the government of the Free State. In another important respect the German model was not followed. Britain, with some partial exceptions, integrated engineering into universities, rejecting the continental model of separate engineering schools.⁷² And from about 1870, British medical schools, which had tended to be separate from universities except in Scotland, became increasingly integrated into universities, first in the provinces and later

⁷¹ The best survey is to be found in Sidney Pollard, *Britain's Prime and Britain's Decline* (London: Arnold, 1989). See also Edgerton, *British Industrial 'Decline'*; Michael Sanderson, "The English Civic Universities and the 'Industrial Spirit,' 1870-1914," *Historical Research*, 61 (1988), 90-105. The latter is a rejoinder to aspects of the now notorious work by Martin Wiener, *English Culture and the Decline of the Industrial Spirit, 1850-1980* (Cambridge: Cambridge University Press, 1981).

⁷²P. Hennock, "Technological Education in England, 1850-1926: the Uses of a German Model," *History of Education*, 19 (1990), 299-331.

in London. Many of the rapidly growing “civic” universities were given independent charters in this period, with the right to examine their own students. Their income came from central and local government, from private donations and endowments, and from student fees (some covered by local government scholarships).⁷³ Some one-third of their students studied medicine. As in much else in this period, the key unit of analysis was not so much the United Kingdom, but rather the Empire, of which the United Kingdom was a key part. As far as education and science was concerned the key parts were the white dominions, which themselves had great British universities, including McGill in Canada, and universities/colleges in Cape Town, Otago, Christchurch, and Sydney.⁷⁴ Thus it was possible for Ernest Rutherford, who graduated in New Zealand, to undertake further study at Cambridge, then to teach at McGill and then Manchester, before returning to Cambridge in 1919.

Most of the scientists, engineers, and medics produced did standard forms of scientific, technical, and medical work. But these years, in Britain as elsewhere, saw a research revolution, though one less well-known and understood than comparable developments in Germany and the United States. This research revolution brought research not only into universities as a general expectation in elite institutions, but also, simultaneously, into

⁷³ On civics see Sanderson, “The English Civic Universities”; on medicine see S. V. F. Butler, “A Transformation of Training: The Formation of University Medical Faculties in Manchester, Leeds, and Liverpool, 1870-84,” *Medical History*, 30 (1986), 115-31.

⁷⁴ Tamson Pietsch, *Empire of Scholars: Universities, Networks and the British Academic World, 1850-1939* (Manchester: Manchester University Press, 2013).

government and industrial scientific and technical services.⁷⁵ These developments were driven in part at least by a lobby for science advocating state support of both higher education and research, and the reform of the state along more technocratic lines.⁷⁶

All the universities during this period saw themselves as at least in part research institutions. We have already noted two Cambridge cases; in London, University College had research schools around William Ramsay in chemistry and Karl Pearson in statistics, to take but two. In Manchester, by the Edwardian period, there were strong research schools -- in chemistry under W. H. Perkin, and in physics under Schuster and then Rutherford.⁷⁷ The key British figure in bacteriology, Sir Almroth Wright, funded his extensive research program at the voluntary St. Mary's Hospital, London not only by his individualistic private practice but also through philanthropic donations and the manufacture of vaccines.⁷⁸

⁷⁵ For the notion of the research revolution see Michael Aaron Dennis, "Accounting for Research: New Histories of Corporate Laboratories and the Social History of American Science," *Social Studies of Science*, 17 (1987), 479-518; David Edgerton, "The Linear Model Did Not Exist: Reflections on the History and Historiography of Science and Research in Industry in the Twentieth Century," in *The Science-Industry Nexus: History, Policy, Implications*, ed. Karl Grandin, Nina Wormbs, and Sven Widmalm (Sagamore Beach: Science History Publications, 2004), pp. 31-57.

⁷⁶ Frank Turner, "Public Science in Britain, 1880-1919," *Isis*, 71 (1980), 589-608.

⁷⁷ Jack Morrell, "W. H. Perkin Jr., at Manchester and Oxford: from Irwell to Isis," *Osiris*, 8 (1993), 104-26; David Wilson, *Rutherford: Simple Genius* (Cambridge, Mass.: MIT Press, 1983).

⁷⁸ Elsbeth Heaman, *St Mary's: The History of a London Teaching Hospital* (Montreal: McGill University Press, 2003); Wai Chen, "The Laboratory as Business: Sir Almroth Wright's Vaccine Programme and the

Research in microbiology, parasitology, entomology, and mycology were central to that other great motor of science ca. 1900 – the “constructive imperialism,” which was meant to extend British political and economic power in Africa and Asia (and parts of South America). In Liverpool, research in tropical medicine and associate disciplines were funded by local ship-owners; in London, the School of Tropical Medicine was government-led.⁷⁹ We know less about the effects of constructive imperialism on physical sciences and engineering.⁸⁰ Research on matters of concern to the state, often partly financed by the

Construction of Penicillin,” in *The Laboratory Revolution in Medicine*, ed. A. Cunningham and P. Williams (Cambridge: Cambridge University Press, 1992).

⁷⁹ Michael Worboys, “Manson, Ross and Colonial Medical Policy: Tropical Medicine in London and Liverpool, 1899-1914,” in *Disease, Medicine and Empire: Perspectives on Western Medicine and the Experience of European Expansion*, ed. Roy M. MacLeod and M. Lewis (London: Routledge, 1988); Lise Wilkinson and Anne Hardy, *Prevention and Cure: the London School of Hygiene and Tropical Medicine: A 20th century Quest for Global Public Health* (London: Kegan Paul, 2001); Michael Worboys, “Science and British Colonial Imperialism 1845-1940” (PhD thesis, University of Sussex, 1976); Biswamoy Pati and Mark Harrison, eds., *Health, Medicine and Empire: Perspectives on Colonial India* (London: Sangam Books, 2001); Shang-Jen Li, “Natural History Of Parasitic Disease,” *Isis*, 93 (2002), 206-28. For economic biology in Britain, see Alison Kraft, “Building Manchester Biology 1851-1963: National Agendas, Provincial Strategies” (PhD thesis, University of Manchester, 2000) and her “Pragmatism, Patronage and Politics in English Biology: the Rise and Fall of Economic Biology 1904-1920,” *Journal of the History of Biology*, 37 (2004), 213-58.

⁸⁰ Daniel Headrick, *The Tools Of Empire* (New York: Oxford University Press, 1981); Daniel Headrick, *The Tentacles Of Progress* (New York: Oxford University Press, 1988). Richard Noakes, “Industrial

state, was a notable feature of these years. The National Physical Laboratory (1900) was financed not just by government but also by fees and private donations.⁸¹

For medical science, Britain had struggled to found a research institute (eventually the Lister Institute) comparable to the Pasteur Institute in Paris, but as concern with infant mortality mounted at the start of the new century, medical research appeared as one means of building a larger, healthier population, and hence a more efficient state. A Medical Research Committee, formed under the 1911 National Insurance Act, was expected to focus on tuberculosis but was soon dominated by Cambridge physiologists who helped establish a presence within government for the elites of British science and education. But here again, mixed finance was crucial. Cancer research was supported by two charities established for that purpose (in 1899 and then in 1923).⁸²

The backwardness of British businesses in research in this period, and indeed later, has been exaggerated in an older historiography overly influenced by contemporary complaints and crude assumptions about the link between research and economic development.⁸³ The

Research at the Eastern Telegraph Company, 1872–1929,” *The British Journal for the History of Science*, 47 (2014), 119–46.

⁸¹ Eileen Magnello, *A Century of Measurement: An Illustrated History of the National Physical Laboratory* (Bath: Canopus, 2000).

⁸² Joan Austoker, *A History of the Imperial Cancer Research Fund 1902–1986* (Oxford: Oxford University Press, 1988).

⁸³ For an example, much quoted, see Cardwell, *Organisation of Science in England*, pp. 204–8; for analysis of the evidence see David Edgerton, “Science and Technology in British Business History,” *Business*

much-analysed loss of synthetic dyes/drugs production to Germany should be seen in context – Germany, for all its graduate chemists, then had little else in the way of chemical industry, and no other country (except Switzerland) developed major research-led firms in this field before the Great War. Yet it is necessary to recognise the significance, in Britain as elsewhere, of the entry of foreign firms, most notably in the newest industries. Already before the Great War, General Electric, Westinghouse, Ford Motor Company, and Eastman Kodak had large British operations, as did some firms of German origin, including Siemens.⁸⁴ Through Henry Dale, the Cambridge bio-medical elite was linked to the Wellcome Physiological Laboratories, supported by Wellcome's pharmaceutical company. These enterprises were established in a free-trading space: Britain was the greatest exporter and importer in the world, trading mainly with Europe and the richer parts of the Americas and Australasia. British industrialists organised research in many fields, from heavy chemicals to dyestuffs, from pharmaceuticals to explosives, often drawing on German models established twenty years earlier.⁸⁵

History, 29 (1987), 84–103. See also Christine MacLeod and Gregory Radick, eds., “Part Special Issue: Owning and Disowning Invention: Intellectual Property and Identity in the Technosciences in Britain, 1870–1930,” *Studies in History and Philosophy of Science*, part A, 44 (2013), 161–300.

⁸⁴ For Metropolitan-Vickers Ltd, see Timothy Cooper, “The Science-Industry Relationship: the Case of Electrical Engineering in Manchester 1914–1960” (PhD thesis, University of Manchester, 2003).

⁸⁵ Geoffrey Tweedale, *Steel City: Entrepreneurship, Strategy and Technology in Sheffield, 1743–1993* (Oxford: Clarendon Press, 1995). For a survey of industrial research, see D. E. H. Edgerton and S. M. Horrocks, “British Industrial Research and Development before 1945,” *Economic History Review*, 47 (1994), 213–38; Fox and Guagnini, *Laboratories, Workshops and Sites*.

In agriculture, state funding for research was seen as an alternative to “tariff reform” – a means of boosting British interests without sacrificing the principle of free trade. Agricultural science was developed together with rural roads through the agency of the Development Commission created in 1909, and some of the money went to the private Rothamsted experimental station.⁸⁶

The decades around 1900 saw a global arms race, and in the armed services too one sees a concern with research and experimentation, as well as the entry of university-trained civilian researchers into military and naval laboratories, including the new Research Department at the Woolwich Arsenal (1902) and the Royal Aircraft Factory (1909).⁸⁷ The dreadnought and super-dreadnought battleships, combining heavy guns and armour plate with analogue computers, elaborate range-finders, radio, oil-burning boilers, steam turbines, and much else, were the creation of the Royal Navy and private arms industry, which was clearly investing in research before the Great War.⁸⁸ In industry more generally, there were many examples of laboratories being established for the development of new

⁸⁶ Paolo Palladino, “Between Craft and Science: Plant Breeding, Mendelian Genetics and British Universities, 1900-1920,” *Technology and Culture*, 34 (1993), 300-23; Keith Vernon, “Science for the Farmer? Agricultural Research in England, 1900-1936,” *Twentieth Century British History*, 8 (1997), 310-33.

⁸⁷ On aeronautical research see Bloor, *Enigma*.

⁸⁸ W. H. McNeill, *The Pursuit of Power: Technology, Armed Force, and Society since A.D. 1000* (Chicago: University of Chicago Press, 1982); R. F. Pocock, *The Early British Radio Industry* (Manchester: Manchester University Press, 1988).

products and processes. Sheffield steel provides a clear example of the development of research before 1914 in a field usually condemned for technical backwardness.

In political discussions, technical experts were heard at the highest levels, and some political-intellectual movements, for example the Fabian Society, embraced a notably scientific form of politics. Party leaders with an interest in science included R. B. Haldane, the noted liberal lawyer (and brother of the physiologist J. S. Haldane), who was a leading figure in university reform, army reform, and the law; and on the conservative side was Arthur Balfour, who was closely connected to Cambridge science. Moreover, a strongly nationalistic/imperialistic, technocratic, and anti-democratic scientific lobby existed in the Edwardian years: national efficiency was the watchword for many reform campaigns, including the eugenics movement which sought to limit the reproduction of the lowest classes, attributing their plight to biological, transmissible inferiority.⁸⁹ Unlike the United States, British eugenics was mostly about class rather than race – though Jewish immigration was an issue. Many public health doctors regarded talk of national degeneration as mythical, and British eugenicists preferred to segregate the mentally

⁸⁹ Turner, "Public Science in Britain"; S. Jacyna, "Science and Social Order in the Thought of A. J. Balfour," *Isis*, 71 (1980), 11-34; Roy M. Macleod, "Science for Imperial Efficiency and Social Change. Reflections on the British Science Guild 1905-1936," *Public Understanding of Science*, 3 (1994), 155-93. Andrew Hull, "Passwords to Power: a Public Rationale for Expert Influence on Central Government Policy-Making: British Scientists and Economists, c1900-1925" (PhD thesis, University of Glasgow, 1994); Pauline Mazumdar, *Eugenics, Human Genetics and Human Failings: The Eugenics Society, Its Sources and Its Critics in Britain* (London: Routledge, 1988).

subnormal rather than sterilise them; but from ca. 1900 through to the 1930s, selective breeding was attractive politics on the left as well as the right.⁹⁰

The Great War and After

The weakness of Britain's science-based *industry* on the eve of the Great War was singled out by scientists at the time, and by historians since, as the cause of relative German success.⁹¹ Worse still, the government was prepared to send scientists to the front to die as common soldiers -- the case of the physicist Henry Moseley became iconic.⁹² The state, in this account, belatedly responded by creating a Department of Scientific and Industrial Research, which then continued into the peace.⁹³ But that story underestimated the centrality of the pre-war military departments and the wartime Ministry of Munitions, and indeed that the pre-war British state had hardly neglected the development of weapons of

⁹⁰ For an account of more technical genetics, see Oren Solomon Harman, *The Man Who Invented the Chromosome: A Life of Cyril Darlington* (Cambridge, Mass.: Harvard University Press, 2004). Gavin Schaffer, *Racial Science and British Society, 1930-62* (London: Macmillan, 2008); Manias, *Race, Science, and The Nation*.

⁹¹ See Bernal, *Social Function*; Rose and Rose, *Science and Society*; Donald S. L. Cardwell, "Science and Technology in World War I," *Proceedings of the Royal Society*, part A, 342 (1975), 447-56.

⁹² J. H. Heilbron, *H. G. J. Moseley* (Berkeley: University of California Press, 1974).

⁹³ Andrew Hull, "War of Words: the 'Public Science' of the British Scientific Community and the Origins of the Department of Scientific and Industrial Research, 1914-16," *British Journal for the History of Science*, 32 (1999), 461-81.

war.⁹⁴ As we have seen that view of the state of affairs before 1914, prominent as it remains in accounts of science in the Great War, is untenable. Yet the older historiography repeated these claims, and focussed on new bodies with limited roles, which had “science” in their titles. The action, however, had been and remained elsewhere, and needs to be traced in works concerning these institutions, rather than those concerned with science policy.⁹⁵

⁹⁴ See the survey by Keith Vernon, “Science and Technology,” in *The First World War in British History*, ed. Stephen Constantine, Maurice Kirby, and Mary Rose (London: Arnold, 1995) and Edgerton, *Warfare State* for further references. See also A. Hull, “Food for Thought?: The Relations between the Royal Society Food Committees and Government, 1915-1919,” *Annals of Science*, 59 (2002), 263-98; Roy M. MacLeod, “Sight and Sound on the Western Front: Surveyors, Scientists and the ‘Battlefield Laboratory’, 1915-1918,” *War & Society*, 18 (2000), 23-46. For the Chemical Warfare case see L. F. Haber, *The Poisonous Cloud: Chemical Warfare in the First World War* (Oxford: Clarendon Press, 1985).

⁹⁵ Thus Michael Sanderson, *The Universities and British Industry* (London: Routledge & Kegan Paul, 1972) is by far the best general treatment of British university science. For state science see the official histories, especially R. Hughes and J. D. Scott, *The Administration of War Production* (London: HMSO, 1956) and M. M. Postan *et al.*, *The Design and Development of Weapons* (London: HMSO, 1964); Margaret Gowing, *Britain and Atomic Energy, 1939-1945* (London: Macmillan, 1964); Margaret Gowing, *Independence and Deterrence: Britain and Atomic Energy 1945-1952*, vol. I: *Policy Making*, vol. II, *Policy Execution* (London, Macmillan, 1974); W. J. Reader, *Imperial Chemical Industries: A History*, vols. 1 and 2 (London: Oxford University Press, 1970, 1975); Martin Campbell-Kelly, *ICL: A Business and Technical History* (Oxford: Clarendon Press, 1989); Jack Morrell, *Science at Oxford 1914-1939: Transforming an Arts University* (Oxford: Clarendon Press, 1997); Hannah Gay, *The History of Imperial College, 1907-2007: Higher Education and Research in Science, Technology and Medicine* (London: Imperial College Press, 2007).

Much of the scientific mobilisation needs to be understood as a response to characteristics of the war that could hardly have been anticipated rather than as a failure to invest in research pre-war. It was a long war, in which Britain was forced to send a mass army, then a conscript army, to the Western Front. It was forced to produce many things it thought best to leave to Germany and its future allies, from synthetic dyes to scientific glassware. On the battlefield it had to cope with unprecedented casualties and new weapons such as gas.⁹⁶

War had been good for research. New linkages had been forged, and through a great variety of state institutions -- whether old, reformed or new -- more money became available. And despite the economic problems of the interwar years, the research enterprise developed strongly. Growth was slower than in the Edwardian years, and there were few institutional innovations, yet the change of scale of activity was very significant. The British armed services created large staffs of civilian researchers collaborating (and sometimes competing) with the technical arms of the forces. Directors of Scientific Research were appointed for the Navy (1920) and the Air Force (1925), though not until 1938 for the Army. Some of the defence laboratories were much bigger than academic laboratories, for example, the Research Department at Woolwich, the Royal Aircraft Establishment at

⁹⁶ Roger Cooter, *Surgery and Society in Peace and War: Orthopaedics and the Organisation of Modern Medicine, 1880-1948* (Basingstoke: Macmillan, 1993); Roger Cooter, Mark Harrison, and Steve Sturdy, eds., *Medicine and the Management of Modern Warfare* (Amsterdam: Rodopi, 1999); Roger Cooter, *War, Medicine and Modernity* (Stroud: Sutton Publishing, 1998).

Farnborough, and the chemical warfare establishment at Porton Down.⁹⁷ And the continued expansion of the empire, together with the greater imperial orientation of trade, supported the development of research in many other fields, from food preservation to locust control, funded by a variety of institutions including the Empire Marketing Board.⁹⁸ New means of communication also benefited; imperialism, radio, and aviation proved highly synergistic.⁹⁹ Even whaling was scientized.¹⁰⁰

Britain was no longer so committed to free trade, and the once-dreaded Protection became a key feature of economic life. Like many new industries of the 1920s, dyestuffs grew up

⁹⁷ On interwar warlike R&D see David Zimmerman, *Britain's Shield: Radar and the Defeat of the Luftwaffe* (London: Sutton, 2000); Rob Evans, *Gassed: British Chemical Warfare Experiments on Humans at Porton Down* (London: House of Stratus, 2000); Edgerton, *Warfare State*, chap. 3.

⁹⁸ Michael Worboys, "Science and British Colonial Imperialism"; Michael Worboys, "British Colonial Science Policy, 1918-1939," in *Les Sciences Coloniales: Figures and Institutions*, ed. P. Petitjean (Paris: ORSTOM, 1996), pp. 99-112; Michael Worboys, "The Imperial Institute, the State and the Development of the Natural Resources of the Colonial Empire, 1887-1923," in *Imperialism and the Natural World*, ed. John M. Mackenzie (Manchester: Manchester University Press, 1990), pp. 164-86; Michael Worboys, "Science and the British Colonial Empire, 1895-1940," in *Science and Empire*, ed. Deepak Kumar (New Delhi: NISTAD, 1990), pp. 13-27; Peder Anker, *Imperial Ecology: Environmental Order in the British Empire, 1895-1945* (Cambridge, Mass.: Harvard University Press, 2001).

⁹⁹ Daniel Headrick, *The Invisible Weapon* (Oxford: Oxford University Press, 1991); David Edgerton, *England and the Aeroplane: An Essay on a Militant and Technological Nation* (Basingstoke: Macmillan, 1991).

¹⁰⁰ D. Graham Burnett, *Sounding of the Whale* (Chicago: University of Chicago Press, 2012).

behind selective import controls.¹⁰¹ Imperial Chemical Industries (ICI), formed in 1926 by the merger of three firms based mainly in the north of England and Scotland, dominated heavy chemicals, explosives, and dyestuffs, and was the largest research-performing firm in the country. Its big projects were in synthetic ammonia (to provide fertilisers for the empire) and coal hydrogenation (to use surplus coal and produce a domestic source of petrol); it recruited its main chemists from Oxford and its engineers from Cambridge. The large electrical concerns, such as Metro-Vickers, GEC, and British Thomson Houston, were also notable for their research and development (R&D), but almost all large manufacturing concerns undertook some research by the later 1930s, mostly in specially assigned laboratories. Characterisations of British industrial research effort in this period as deficient, over-dependent on “research associations” funded by the DSIR (Department of Scientific and Industrial Research, an institution established by the government at the beginning of the First World War to support and help coordinate scientific industrial research) and failing to follow the German and especially U.S. model of large corporate research laboratories, seem to derive from underestimates of the scale of industrial research

¹⁰¹L. F. Haber, “Government Intervention at the Frontiers of Science: British Dyestuffs and Synthetic Organic Chemistry 1914-1939,” *Minerva*, 11 (1973), 79-94.

and its significance for British firms.¹⁰² The real scale and scope of interwar research is not evident in the campaigns of the interwar scientists' movement.¹⁰³

Much of the better-known government-funded research was effectively controlled by civilian scientists who sat on the Medical Research Council (MRC), the Department of Scientific and Industrial Research, and the Development Commission, founded before or during the war.¹⁰⁴ Importantly, and controversially, such bodies were attached to the center of government, rather than to ministries with specific functions; they enjoyed an autonomy denied to research divisions that reported directly to the military ministries or

¹⁰² See in particular the arguments of David Mowery, "Industrial Research," in *The Decline of the British Economy*, ed. B. Elbaum and W. Lazonsick (Oxford: Oxford University Press, 1986). See Edgerton, "Science and Technology in British Business History" and Edgerton and Horrocks, "British Industrial Research and Development before 1945," for references to work which refutes the thesis.

¹⁰³ Of particular note is the work of Roy MacLeod, and that of his students, for example Roy M. Macleod and K. Macleod, "The Social Relations of Science and Technology 1914-39," in *Fontana Economic History of Europe*, vol. 5: *The Twentieth Century*, ed. C. Cipolla (Brighton: Harvester Press, 1977), pp. 301-63; Roy M. Macleod and Kay Macleod, "The Contradictions of Professionalization: Scientists, Trade Unionism and the First World War," *Social Studies of Science*, 9 (1979), 1-32; Roy M. Macleod and Peter Collins, eds. *The Parliament of Science: The British Association for the Advancement of Science 1831-1981* (Northwood: Science Reviews, 1981). On scientists' movements see William McGucken, *Scientists, Society and the State: The Social Relations of Science Movement in Great Britain, 1931-1947* (Columbus: Ohio State University Press, 1984).

¹⁰⁴ Ian Varcoe, *Organizing for Science in Britain: A Case Study* (London: Oxford University Press, 1974). Joan Austoker and Linda Bryder, eds., *Historical Perspectives on the Role of the MRC: Essays in the History of the Medical Research Council of the United Kingdom and its Predecessor, the Medical Research Committee, 1913-1953* (Oxford: Oxford University Press, 1989).

the new Ministry of Health.¹⁰⁵ All the research councils placed a great emphasis on what they called “fundamental” science, a term with a particular meaning.¹⁰⁶ Some of the research they funded was carried out in universities, some in semi-private institutions like the Rothamsted agricultural laboratories or the Lister (medical) Institute, and some in laboratories owned by the funding agencies themselves, the largest of which was the National Physical Laboratory (now firmly within government, under the DSIR).¹⁰⁷ Both contemporaries and historians have asked whether there was much connection between this “fundamental” state-science and the practices of the hospital, the farm, and the factory.¹⁰⁸ Many leading clinicians were suspicious of the MRC and resentful of its condescension towards the “empiricism” of practice; they believed research ought to be led by clinical problems, whereas the MRC expected medical improvement to flow from laboratory experimentation and analysis as exemplified by the (Canadian) discovery of

¹⁰⁵ The rationalisation of the distinction between the research done by departments themselves and the bodies like the MRC and DSIR was made by Lord Haldane in 1918. The “Haldane principle,” a mish-mash of confused analyses, coined in 1964, is something different and has bedevilled writing on science and the British state since then.

¹⁰⁶ Sabine Clarke, “Pure Science with a Practical Aim: The Meanings of Fundamental Research in Britain, circa 1916–1950,” *Isis*, 101 (2010), 285–311.

¹⁰⁷ Russell Moseley, “The Origins and Early Years of the National Physical Laboratory: A Chapter in the Prehistory of British Science Policy,” *Minerva*, 16 (1978), 222–50; Russell Moseley, “Government Science and the Royal Society: The Control of the National Physical Laboratory in the Interwar Years,” *Notes and Records of the Royal Society of London*, 35 (1980), 167–93; Philip Chaston, “Gentlemanly Professionals within the Civil Service: Scientists as Insiders during the Inter-war Period” (PhD thesis, University of Kent, 1998).

¹⁰⁸ Paolo Palladino, “Between Craft and Science”; Keith Vernon, “Science for the Farmer?”

insulin. To extend their research ethos into medical practice, the MRC pushed for research clinicians to be appointed to University hospitals, and they used American precedents and funds. But since private consultant practice was much more remunerative than professorial salaries, clinical research remained marginal in Britain until the establishment of the National Health Service (NHS) after WWII.¹⁰⁹ For example, though the MRC could point to successes in the small medical school at Sheffield, in the larger provincial schools such as Manchester, advocates of salaried clinical research were repeatedly frustrated by financial stringency and by the reluctance of their protégés to reduce their private practices. Much of the research in medical schools was funded though philanthropic foundations based on new industrial money. The Rockefeller Foundation (based in the United States) promoted public health programs, clinical research, and the application of physics and chemistry to the understanding of living materials.¹¹⁰ William Morris, the Oxford car manufacturer who set up the Nuffield Trust,

¹⁰⁹ Austoker and Bryder, *Historical Perspectives*; Steve Sturdy, "The Political Economy of Scientific Medicine: Science, Education and the Transformation of Medical Practice in Sheffield, 1890-1922," *Medical History*, 36 (1992), 125-59; Helen K. Valier, "The Politics of Scientific Medicine in Manchester, c 1900-1960" (PhD thesis, University of Manchester, 2002); Andrew Hull, "Hector's House: Sir Hector Hetherington and the Academicization of Glasgow Medicine before the NHS," *Medical History*, 45 (2001), 207-42.

¹¹⁰ Robert E. Kohler, *From Medical Chemistry to Biochemistry: The Making of a Biomedical Discipline* (Cambridge: Cambridge University Press, 1982); Richard E. Brown, *Rockefeller Medicine Men: Medicine and Discipline In America* (Berkeley: University of California Press, 1979).

was especially generous to his local University. It seems that in the late 1930s the MRC and charities each contributed about £200,000 per annum to medical research.¹¹¹

From the 1920s, the elite universities also received substantial funding from central government, including the University Grants Committee and the “research councils,”¹¹² and with increased funding came a much larger scale of university research. By the 1930s, as J. D. Bernal noted, British university laboratories housed around 1500 research students and some 100 research fellows.¹¹³ These, however, were distributed very unevenly both between subjects and between sites; research was largely in “science” rather than “technology.” Chemistry, physics, and mathematics were favored, and there were great differences between universities. The strength of Cambridge was quantitative as well as qualitative; it became the center of pure science, famous for nuclear physics in the Cavendish laboratory, and for physiology and its new daughter, biochemistry. In chemistry the key centers now included Oxford, as well as the large civic universities and London; most of the department heads had trained outside Oxbridge, and often also in Germany. By the mid-thirties, University College London’s chemistry laboratory had two professors, two readers, two senior lecturers, and seven lecturers; it turned out more than ten PhDs every year.¹¹⁴

¹¹¹ Bernal, *Social Function*, pp. 49-50.

¹¹² Morrell, *Science at Oxford*; Anker, *Imperial Ecology*.

¹¹³ Bernal, *Social Function*, p. 37.

¹¹⁴ Gerrylyn Roberts, “C. K. Ingold at University College London: Educator and Department Head,” *British Journal for the History of Science*, 29 (1996), 65-82; G. K. Roberts, “Physical Chemists for Industry, The

One important consequence of industrial shifts and the greater involvement of the central state in teaching and research was a geographical redistribution of research and innovation. By comparison with the nineteenth century, Scotland now figured less strongly as a site for research and the development of new industries. The great civic universities of the north of England also lost some proportionate strength with the decline of their older local trades and the spread of new industries in the midlands and the south. Industrial combines with headquarters in London tended to build their laboratories in the south east, which is where most of the government's military and civil laboratories were located, including those for medicine and agriculture. As business came to be recognised as a graduate career, so major companies became more involved with socially elite universities, and the late Victorian linkage of useful-science with the provinces weakened. All these tendencies benefited Oxford and Cambridge, where academic modernisers were keen to recruit research school leaders, often from the provinces.

The culture of independent Ireland was notably less scientific than that of Scotland or indeed Wales, despite the efforts of the mathematician President Eamonn De Valera and his Dublin Institute of Advanced Studies. After 1922, the new Irish Free State dropped out of the British funding system but failed to establish a strong research base of its own. Its favored universities were dominated by nationalists and Catholics with little sympathy for the largely Protestant "modernisers," or for the persistently protestant tradition of Trinity

Making of the Chemist at University College London, 1914-1939," *Centaurus*, 39 (1997), 291-310. See also the online database of British chemists being compiled by Gerrylyn Roberts.

Commented [HS4]: Catholics and protestant in Caps?

College, Dublin. Irish nationalism chose to pursue policies that directly and indirectly distanced Irish nationalism from science,¹¹⁵ and scientific Irishmen still tended to seek careers in Britain – J. D. Bernal and E. T. Walton being important cases.¹¹⁶

In the later nineteenth century, most science graduates went into teaching; only chemistry had afforded substantial professional employment for its practitioners. By the interwar period, physics and biomedical disciplines were also recognised as scientific professions, providing manpower not just for research but for all the monitoring that was becoming integral to medicine and agriculture as well as new industry. The vast majority of industrial scientists were occupied with analytical work and quality control; and the research councils had large programs on standardisation – for example the MRCs concern with the standardisation of biological therapies such as vaccines and insulin. Nor should we neglect the colonial natural historical surveys and pest management programs for empire.¹¹⁷

¹¹⁵ Greta Jones, “Catholicism, Nationalism and Science,” *The Irish Review*, 20 (1997), 47-61.

¹¹⁶ Roy Johnston, “Irish Roots,” in *J.D. Bernal: A Life in Science and Politics*, ed. Brenda Swann and Felix Aprahamian (London: Verso, 1999).

¹¹⁷ Anker, *Imperial Ecology*; Michael Worboys, “Science and British Colonial Imperialism, 1895-1940” (PhD, University of Sussex, 1979); Roy M. MacLeod, ed., *Nature and Empire: Science and the Colonial Enterprise, Osiris*, 15 (2001); and see the chapter on “Science and Imperialism since 1870” by Michael Worboys and Pratik Chakrabarti in this volume. Helen Tilley, *Africa as a Living Laboratory: Empire, Development, and the Problem of Scientific Knowledge, 1870-1950* (Chicago: University of Chicago Press, 2011).

Private philanthropic endeavours still mattered in the interwar years.¹¹⁸ By the interwar years neither the industrial chemist nor the secondary school science teacher, nor the imperial agricultural or forestry officer was a novelty; they were established roles in a growing technical middle class, about which we know little. A significant proportion of them were women, especially in the biological sciences, though until after WWII marriage usually prevented further employment. Science, one could say, was now a mode of employment, not just an interest, a school subject or a form of belief.

Associations with new industries such as chemicals, aviation, electricity, and radio, increased the ascendancy of science, though it is worth noting that the rate of growth of universities was much lower than for the period 1890-1914. And for some industrialists and politicians a scientific approach to industry seemed to offer an escape from the deep class antagonisms evident from ca. 1916 to the failed General Strike of 1926. Alfred Mond, one of the founders of giant chemical firm ICI gave his name to plans for corporate rationalisation and constructive engagement with labor -- a centrist program that could also be seen in parts of the scientific community.¹¹⁹ In the 1920s, Britain, as a victorious power, was no longer threatened by Germany; the challenges and the models for the old country now came increasingly from the United States, not least from its industry and its industrial funding for research.

¹¹⁸ Michael Bresalier and Michael Worboys, "'Saving the Lives of our Dogs': The Development of Canine Distemper Vaccine in Interwar Britain," *The British Journal for the History of Science*, 47 (2014), 305-34.

¹¹⁹ Werskey, *Visible College*.

The 1930s were a different matter, as the depression undermined the legitimacy of laissez faire capitalism and provided a startling contrast between the collapsing liberal powers and the transformed powers of continental Europe: Nazi Germany and the Soviet Union. For some younger academic scientists, as for intellectuals more generally, the 1930s were a decade of mobilisation, theoretical experimentation, and action. Britain produced a remarkable group of scientist-activists – including Lancelot Hogben, Herman Levy, J. D. Bernal, Patrick Blackett, J. B. S. Haldane and Joseph Needham.¹²⁰ Though they were always a minority, the scientific left of the 1930s were part of a vibrant new “Anglo-marxist” culture,¹²¹ and the accounts they wrote of British science and technology proved influential in the 1960s and 1970s. Yet it is important not to overlook the great significance of liberal and liberal internationalist thinking and practice in relation to science and technology in the interwar years.¹²²

¹²⁰ Werskey, *Visible College*; McGucken, *Scientists, State and Society*; Anna-K. Mayer, “‘A Combative Sense of Duty’: Englishness and the Scientists,” in *Regenerating England: Science, Medicine, and Culture in Interwar Britain*, ed. Christopher Lawrence and Anna-K. Mayer (Amsterdam: Rodopi, 2000), especially pp. 81-3.

¹²¹ Edwin A. Roberts, *The Anglo-Marxists: A Study in Ideology and Culture* (Lanham, Md.: Rowman and Littlefield, 1997).

¹²² Waqar H. Zaidi, “‘Aviation Will Either Destroy or Save Our Civilization’: Proposals for the International Control of Aviation, 1920-45,” *Journal of Contemporary History*, 46 (2011), 150-78. Zaidi, Waqar, “Liberal Internationalist Approaches to Science and Technology in Interwar Britain and the United States,” in *Internationalism Reconfigured: Transnational Ideas and Movements Between the Wars*, ed. Daniel Laqua (London: IB Tauris, 2011), pp. 17-43. Peter Bowler, *Science for All: The Popularization of Science in Early Twentieth-century Britain* (Chicago: University of Chicago Press, 2009), Chris Manias, “Sinanthropus in Britain: Human Origins and International Science, 1920–1939,” *The British Journal for*

The Second World War

For the Second World War as for the Great War, the old standard story of British science centers on the drafting of *academic* scientists into the war effort, now with a particular emphasis on radar, the atomic bomb, and “operational research.”¹²³ Again this account neglected pre-existing military scientific organisations, though these were much larger in 1939 than in 1914.¹²⁴ For the Second World War a small number of academic scientists, plus large numbers of recent graduates, were recruited into pre-existing R&D programs, which were hugely expanded. Most of the famous innovations in military technique came from state servants and their new recruits, rather than from seconded academics: radar was developed by government radio experts; the jet engine by civil servants and an RAF officer, Frank Whittle; and sonar (ASDIC) by naval scientists. Many academics and young scientists were also recruited into long established projects in aeronautics, poison gas, explosives, ballistics, and so on. In distinct contrast to the United States, the universities did not become major R&D contractors; military R&D was carried out almost exclusively

the History of Science, 48 (2015), 289-319. Jeff Hughes, “‘Divine Right’ or Democracy? The Royal Society ‘Revolt’ of 1935,” *Notes and Records of the Royal Society*, 64 (2010), S101-S117.

¹²³ See Rose and Rose, *Science and Society*; Angus Calder, *People’s War* (London: Cape, 1969), chap. 8. See also William McGucken, “The Central Organisation of Scientific and Technological Advice in the United Kingdom During the Second World War,” *Minerva*, 17 (1979), 33-69; McGucken, *Scientists, Society and the State*.

¹²⁴ Thomas, *Rational Action*.

in government laboratories and private firms. Universities continued essentially as teaching bodies, turning out graduates, often on accelerated courses.¹²⁵

The standard accounts also overestimate the role of high profile academics like Bernal, Blackett, and Zuckerman. They were involved primarily in operational research, which was peripheral to the main R&D effort, where *academic* scientists rarely held the top posts.¹²⁶ Though academic scientists came to head the old Woolwich research department, which would later create the British atomic bomb, and the army radar effort, newer enterprises such as the Telecommunications Research Establishment (the key radar laboratory) and the Royal Aircraft Establishment remained in the hands of pre-war scientific civil servants.¹²⁷

Industry was also involved, even in the most academic of wartime innovations – penicillin and the atomic bomb. Consider penicillin, where an initially fruitless discovery by Alexander Fleming at a London voluntary (charity) hospital was taken up in Oxford by Howard Florey in his MRC-funded survey of natural antibacterial substances. The project

¹²⁵ Edgerton, *Warfare State*; David Edgerton, *Britain's War Machine: Weapons, Resources and Experts in the Second World War* (London: Allen Lane, 2011).

¹²⁶ Paul Crook, "Science and War: Radical Scientists and the Tizard-Cherwell Area Bombing Debate in Britain," *War & Society*, 12 (1994), 69-101; Erik P. Rau, "Technological Systems, Expertise and Policy Making: the British Origins of Operational Research," in *Technologies of Power: Essays in Honor of Thomas Parke Hughes and Agatha Chipley Hughes*, ed. Michael Allen and Gabrielle Hecht (Cambridge, Mass.: MIT Press, 2001), both pieces particularly focussing on the role of the left.

¹²⁷ Edgerton, *Warfare State*, chap. 4.

was then boosted by war-time funding and transferred to industry for production. The British pharmaceutical companies and ICI were closely involved and produced penicillin on a substantial scale, but U.S. universities and companies were able to steal a march, and establish patents, through their greater experience of large-scale fermentation.¹²⁸ The British bomb project was also conducted both in university laboratories (with a high proportion of refugee scientists) and in industry (with ICI taking a leading role); indeed, within government, the project was run by an ICI, Oxford-trained chemist.¹²⁹ This huge project was also later transferred to the United States and Canada, where major industrial corporations and the U.S. Army Corps of Engineers both played important roles. Yet the biggest and most neglected projects were in the aircraft industry, for example in the development of many different types of jet engine.¹³⁰

However produced, the results became icons of British brilliance, and they helped give science and technology a new place in public culture. Science was respected, even feared. For the MRC, penicillin was strong evidence for the support of basic research and for national planning; for many others it became a tale of national loss through failure to control exploitation; and at the end of the war, when the NHS was imminent and the

¹²⁸ Gwyn Macfarlane, *Howard Florey: The Making of a Great Scientist* (Oxford: Oxford University Press, 1979); Gwyn Macfarlane, *Alexander Fleming: The Man and the Myth* (Oxford: Oxford University Press, 1985); Heaman, *St Mary's*; Jonathan Liebenau, "The British Success with Penicillin," *Social Studies of Science*, 17 (1987), 69-86.

¹²⁹ Margaret Gowing, *Britain and Atomic Energy*.

¹³⁰ Giffard, *Making Jet Engines*.

nationalisation of the chemical industry a real possibility, Fleming's discovery was used in defence of British voluntarism.¹³¹

As never before, Britain saw itself as a scientific nation, and the arguments for more science in national life, associated particularly with the scientific left, became truisms.¹³² The wartime expansion of research activity continued into the peace and was linked to a similar growth in development, indeed they came closer together, as the increasing use of the term "research and development" or R&D suggested. The challenges and models for Britain now lay in the new superpowers -- the United States and the Soviet Union. Into the early 1960s, British expenditure on scientific R&D (relative to output) was a good third behind the superpowers, though well in advance of the former great powers.

The Nationalization of Research and Development

Most studies of post-war Britain are organised round the "rise of the welfare state," but, for the promotion of research, *welfare* was less important than *warfare* and the industrial

¹³¹ Robert Bud, "Penicillin and the New Elizabethans," *British Journal for the History of Science*, 31 (1998), 305-13. Heaman, *St Mary's*.

¹³² Edgerton, *Britain's War Machine*; Edgerton, *England and the Aeroplane*; Sophie Forgan, "Festivals of Science and the Two Cultures: Science, Design and Display in the Festival of Britain, 1951," *The British Journal for the History of Science*, 31 (1998), 217-40; Bud, "Penicillin"; Hermione Giffard, "The Politics of Donating Technological Artifacts: Techno-nationalism and the Donations of the World's First Jet Engines" *History and Technology*, 30 (2014), 61-82; James Sumner, "Defiance to Compliance: Visions of the Computer in Postwar Britain," *History and Technology*, 30 (2014), 309-33.

development that was partly driven by nationalistic economic policies. Imports were systematically discouraged, and local designs and supplier sources preferentially used.¹³³ Science and the nation, science and nationalism, marched together. Perhaps the key feature of the post-Second World War years was the dominance of the national government -- through a greatly expanded military sector together with the nationalisation of public utilities, key industries such as coal and steel, and the hospitals. National agriculture was expanded very significantly by direct and indirect subsidy, including money for scientific research; even in plant breeding, government funding came to dominate the four important institutions that had in the past received only part of their income from the state.¹³⁴ And the new Colonial Research Council spent more than the MRC or the Agricultural Research Council,¹³⁵ partly because of the drive for the better exploitation of raw materials, symbolised by the ambitious African groundnut scheme of the late 1940s, part of the

¹³³ A. S. Milward and G. Brennan, *Britain's Place in the World: A Historical Enquiry into Import Controls, 1945-1960* (London: Routledge, 1996).

¹³⁴ Paolo Palladino, "Science, Technology and the Economy: Plant Breeding in Great Britain, 1920-1970," *Economic History Review*, 49 (1996), 137-53. Hannah Gay, "Before and After Silent Spring: From Chemical Pesticides to Biological Control and Integrated Pest Management - Britain, 1945-1980," *Ambix*, 59 (2012), 88-108.

¹³⁵ Sabine Clarke, "A Technocratic Imperial State? The Colonial Office and Scientific Research, 1940-1960," *Twentieth Century British History*, 18 (2007), 453-80; Sabine Clarke, "Specialists or Generalists? Scientists, the Colonial Office and the Development of the British Colonies, 1940-1960" (PhD thesis, University of London, 2005).

“second colonisation” of Africa.¹³⁶ The years after the Second World War were the great years of scientific research and scientific extension services in the Empire.¹³⁷

In the first two post-war decades Britain maintained very high R&D spending – civilian and military, public and private – and compared with the rest of Western Europe its higher education system was peculiarly oriented towards science and technology. The proportion of national income devoted to R&D was much higher than that of any capitalist nation other than the United States, and British businesses were second only to those of the United States in absolute and relative commitment to industrial research.¹³⁸ From 1945 to 1974 British scientists won, on average, more than one Nobel Prize each year, a much better record than in the first half of the century. But, for all this strength, who could doubt that the world center of scientific, technical, and medical innovation had passed from Europe to the United States? America, much more than Britain was the model for post-war scientific reconstruction in continental Europe; and it became common for young British researchers to spend time in the United States.

But at the end of the war, the scale of British warlike research and development hardly diminished as the government committed to new generations of armaments, including

¹³⁶ David Cantor, “Cortisone and the Politics of Drama,” in *Medical Innovations in Historical Perspective*, ed. John V. Pickstone (Basingstoke: Macmillan, 1992).

¹³⁷ Joseph Morgan Hodge, *Triumph of the Expert: Agrarian Doctrines of Development and the Legacies of British Colonialism* (Athens: Ohio University Press, 2007); Tilley, *Africa as a Living Laboratory*.

¹³⁸ Edgerton, *British Industrial ‘Decline’*.

nuclear, chemical, and biological weapons; demobilisation was minimal. And from around 1950, rearmament brought huge increases in military R&D spending, overwhelmingly in government and industry.¹³⁹ As a result, in the mid-1950s some 80 percent of government R&D, and 60 percent of all British R&D was military. Though most was done in industry, national laboratories became increasingly important. The civil atomic program was developed in a new state laboratory at Harwell, while the bomb was designed at the army's main research laboratory, and then at a new state laboratory at Aldermaston. At Porton Down, work on chemical warfare was supplemented with an important program on biological weapons.¹⁴⁰ The aeronautical and electronic laboratories were also expanded. Again and again we find the belief that brilliant Britain could design innovative aeroplanes, nuclear reactors, and electronic devices that would leapfrog the more intensive but

¹³⁹ Gowing, *Britain and Atomic Energy*; Gowing, *Independence and Deterrence*; Peter Morton, *Fire Across the Desert: Woomera and the Anglo-Australian Joint Project 1946-1980* (Canberra: Department of Defence, 1989); Edgerton, *England and the Aeroplane*; S. R. Twigge, *The Early Development of Guided Weapons in the United Kingdom 1940-1960* (Amsterdam: Harwood Academic, 1993); Jon Agar and Brian Balmer, "British Scientists and the Cold War: The Defence Research Policy Committee and Information Networks, 1947-1963," *Historical Studies in the Physical Sciences*, 28 (1998), 1-40; Robert Bud and Philip Gummett, eds, *Cold War, Hot Science: Applied Research in Britain's Defence Laboratories, 1945-1990* (Harwood Academic, 1999); Brian Balmer, *Britain and Biological Warfare: Expert Advice and Science Policy, 1930-1965* (London: Palgrave, 2001); Lorna Arnold, *Britain and the H-Bomb* (London: Palgrave, 2001); James Small, *The Analogue Alternative: The Electronic Analogue Computer in Britain and the USA, 1930-1975* (London: Routledge, 2001); Edgerton, *Warfare State*. Andrew Pickering, *The Cybernetic Brain: Sketches of Another Future* (Chicago: University of Chicago Press, 2010).

¹⁴⁰ Robert Bud, *The Uses of Life: A History of Biotechnology* (Cambridge: Cambridge University Press, 1994).

plodding efforts of the Americans.¹⁴¹ Those in charge were government scientists not academics.¹⁴² In 1949 Britain clearly considered itself the second great technological power, but the explosion of the Soviet atomic device in that year led to some downgrading of this assessment.

It is sometimes argued that this expenditure on weapons was at the expense of bread and butter civil development, and that Germany and Japan, no longer world powers, were able to outspend Britain on such R&D; however, this common place of commentary is untenable.¹⁴³ Industrially funded research and development boomed from the end of the war, and into the mid-1960s it was absolutely and relatively greater than that of German or Japanese industry.¹⁴⁴ Furthermore, British industry distributed its effort across different fields in much the same way as the Germans and the Japanese.

¹⁴¹ Edgerton, *England and the Aeroplane*.

¹⁴² Edgerton, *Warfare State*; Alexandros Oikonomou, "The Hidden Persuaders: Government Scientists and Defence in Post-war Britain" (PhD thesis, University of London, 2011).

¹⁴³ For details see Edgerton, *British Industrial Decline*, and David Edgerton, "The 'White Heat' Revisited: The British Government and Technology in the 1960s," *Twentieth Century British History*, 7 (1996): 53-82. The argument itself is widespread, but its most influential expression is probably Christopher Freeman, "Technical Innovation and British Trade Performance" in *De-Industrialisation*, ed. F. T. Blackaby (London: Heinemann, 1979).

¹⁴⁴ Sally M. Horrocks, "Enthusiasm Constrained? British Industrial R&D and the Transition From War to Peace, 1942-51," *Business History*, 41 (1999), 42-64.

Many of the new clinical researchers collaborated with the pharmaceutical companies, which greatly expanded their research activities; ICI moved into pharmaceuticals, including new anaesthetics, partly from its experience in the war-time collaborations over fluorine chemistry and penicillin.¹⁴⁵ A wartime committee on medical education proved successful in boosting pre-clinical sciences in universities, thus strengthening research as well as teaching. However, it proved less successful in its advocacy of “social medicine,” a discipline meant to incorporate social sciences into clinical medicine and so rescue public health from the local authority medical-bureaucrats.¹⁴⁶ The MRC was particularly keen to support biophysics and helped several war-time physicists to enter this new field, so encouraging the x-ray crystallography and membrane physiology for which Cambridge and London Universities, especially, were already known.¹⁴⁷ They also funded much more clinical research and helped build up academic departments in teaching hospitals. Some of these departments then collaborated with the pharmaceutical companies, developing antibiotics and then new drugs for psychiatric and cardio-vascular diseases. For the first time, Britain was now a major player in the international drug industry.¹⁴⁸

¹⁴⁵ J. Beinart, *A History of the Nuffield Department of Anaesthetics, Oxford, 1937-1987* (Oxford: Oxford University Press, 1987); Reader, *Imperial Chemical Industries*.

¹⁴⁶ Dorothy Porter, “Changing Disciplines: John Ryle and the Making of Social Medicine in the 1940’s,” *History of Science*, 30 (1992), 137-164; Weatherall, *Gentlemen, Scientists, and Doctors*.

¹⁴⁷ Soraya de Chadarevian, *Designs for Life: Molecular Biology after World War II* (Cambridge: Cambridge University Press, 2001).

¹⁴⁸ Austoker and Bryder, *Historical Perspectives*.

The 1960s and 1970s saw important changes in the administration of government research. Perhaps the most important was the shift of control from scientific organisations to mainline ministries. Thus the DSIR was broken up, with much going to the Ministry of Technology, while the remainder went, as a research council, along with the others, into the Department of Education and Science. For the government laboratories the mid-1960s saw the beginning of retrenchment and increasing control by users. In 1970 the Labour government proposed the creation of a British Research and Development Corporation to be funded largely on a contract basis, covering most civil research. It did not happen, but following the Rothschild Report, the customer-contractor principle was formally applied to government-funded applied research in the departments. It is telling that on the defence side 1971 saw the setting up of a Procurement Executive, tasked with being an intelligent customer of material and research. The Rothschild Report endorsed the research council system, outside the customer-contractor principle, with two exceptions. These were that a small proportion of the research of two research councils, in agriculture and health, should be done under contract from the relevant ministries.¹⁴⁹ This proposal has led to the erroneous belief that Rothschild represents a major break in research policy (meaning here policy for the research councils), an overturning of something called the “Haldane Principle.” It did not, and in fact the Haldane Principle, meaning something like scientists’ control of government funded research, was an invention of the 1960s. Rightly, Rothschild had noted that the so-called Haldane Principle was not relevant.

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¹⁴⁹ *A framework for government research and development* Parliamentary Papers, 1971-72, Cmnd. 4814

[This contains the Rothschild and Dainton Reports]/.

The "Haldane Principle" was invented in 1964 by Lord Hailsham, as something that was being violated in 1964 with the disbandment of the DSIR and the removal of the Lord President from control of the research councils.¹⁵⁰ Many analysts continue to believe it was a principle formulated in 1918 and which continued, long after 1964, and which stated that scientists should control government-funded research. Such a principle never existed, except in discussions of science policy, seriously misleading analysts as to the nature of government funded research.

The nationalisation of research and development went hand in hand with an incremental nationalisation of the universities. The huge new demand of the state and industry for scientists, engineers, and to a lesser extent doctors, led to a radical expansion of higher education, especially in London and the major civic universities, which were now funded largely by central government. By the 1960s, universal funding for student maintenance as well as fees meant that all universities were, for the first time, overwhelmingly dedicated to full-time residential education geared towards the three-year honours degree (or four in Scotland). By this time the majority of *male* graduates studied science, engineering, or medicine. While at the beginning of the century, churchmen, lawyers, and doctors had dominated the professional middle classes, by 1940 they accounted for about half the total, their numbers having remained static while those of scientists, and especially engineers, had risen rapidly.

¹⁵⁰ On the invention of the Haldane Principle see David Edgerton, "The 'Haldane Principle' and Other Invented Traditions in Science Policy," *History & Policy* Policy Paper, 2 July 2009. Online.

State funding for research in universities increased massively; for academic scientists the 1950s and 1960s were a golden age. Many new fields built directly on war-projects and equipment, from digital computing and radio astronomy to nuclear power and antibiotics, and a self-confident and creative scientific élite moulded the great universities, not least through the experience of administration and command that many young scientists had gained in the war. In terms of public recognition and achievement, perhaps the most famous British developments were in X-ray crystallography applied to molecular biology: from Maurice Wilkins and Rosalind Franklin in London, to James Watson and Francis Crick in Cambridge, and to the elucidation of the structures of other large molecules by Max Perutz, John Kendrew, and the biochemist Fred Sanger.¹⁵¹ In physics, the acclaimed successes were in theoretical cosmology, and in radio astronomy – from Manchester's Jodrell Bank, to the rather different Cambridge work.¹⁵² In ecology and population biology a distinctive school became influential in science policy.¹⁵³ Both these Universities also attracted attention for work on electronic computers. But of course, the public successes were a tiny proportion of the total academic research about which we as yet know very little, historically. Yet there is no doubt that British academic research was enormously

¹⁵¹ Chadarevian, *Designs for Life*.

¹⁵² Jon Agar, *Science and Spectacle: The Work of Jodrell Bank in Post-War British Culture* (Amsterdam: Harwood Academic Press, 1998). Jon Agar, "The New Price and Place of University Research: Jodrell Bank, NIRNS and the Context of Post-War British Academic Science," *Contemporary British History*, 11 (1997), 1-30.

¹⁵³ Hannah Gay, *The Silwood Circle: A History of Ecology and the Making of Scientific Careers in Late Twentieth-Century Britain* (London: Imperial College Press, 2013).

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productive in the years after the Second World War; in the history of almost all disciplines, one has to consider the British contributions.

Ideologues and ideologies

The scientific left of the 1930s were active into the 1940s, before foundering in what E. P. Thompson has called a post-war “NATOpolitan” culture, like most of the rest of this tradition.¹⁵⁴ Scientific intellectuals dissembled to the point of mendacity about the relations of science and war.¹⁵⁵ In the three post-war decades, the dominant ideological tone of science, like that of political culture more generally, was broadly social democratic and technocratic, with a particular emphasis on the need for national modernisation programs. The relative economic decline of Britain, now being dated from 1870s, was commonly blamed on a failure to invest in science and technology. And in C. P. Snow’s “two cultures”

¹⁵⁴ For the politics of science in and through the Royal Society, see Peter Collins, *The Royal Society and the Promotion of Science Since 1960* (Cambridge: Cambridge University Press, 2015); Jeff Hughes, “Doing Diaries: David Martin, the Royal Society and Scientific London, 1947-1950,” *Notes and Records of the Royal Society*, 66 (2012), 273-94.

¹⁵⁵ Werskey, *Visible College*; Greta Jones, *Science, Politics and the Cold War* (London: Routledge, 1988); David Edgerton, “British Scientists and the Relations of Science and War in Twentieth Century Britain,” in *National Military Establishments and the Advancement of Science: Studies in Twentieth Century History*, ed. Paul Forman and J. M. Sanchez Ron (Dordrecht: Kluwer, 1996); Ralph Desmarais, “Jacob Bronowski: A Humanist Intellectual for an Atomic Age, 1946–1956,” *The British Journal for the History of Science*, 45 (2012), 573-89.

polemic and elsewhere,¹⁵⁶ the British political class was presented as aristocratic and amateur -- hostile to science and engineering, careless of economic growth.¹⁵⁷ It was claimed that anti-scientific traditions were behind the anti-nuclear and environmental movements.¹⁵⁸ This kind of thinking reached its highpoint during the Labour government of 1964-1970; Prime Minister Harold Wilson's "White Heat of the scientific revolution" is usually taken as the major peacetime technocratic initiative in British history, and one that failed.¹⁵⁹

It is explicit or implicit in most commentary that Britain's technocratic tradition, where it existed, was on the left. But a new scientific left – much less élite and much more critical of science – emerged in the 1960s, notably around the British Society for Social

¹⁵⁶ On this see Guy Ortolano, *The Two Cultures Controversy: Science, Literature and Cultural Politics in Postwar Britain* (Cambridge: Cambridge University Press, 2009); David Cannadine, "The Two Cultures: the Age of Snow, Todd and Plumb," in *Christ's - A Cambridge College Over Five Centuries*, ed. David Reynolds (London: Macmillan, 2005); Edgerton, *Warfare State*; special issue of *History of Science* on "Two Cultures?," 43 (June 2005), part 2, with contributions from Theodore M. Porter, Paul White, Anna-K. Mayer, Guy Ortolano, and David Edgerton.

¹⁵⁷ Norman J. Vig, *Science and Technology in British Politics* (Oxford: Pergamon, 1968); and Norman J. Vig, "Policies for Science and Technology in Great Britain: Postwar Development and Reassessment," in *Science Policies of Industrial Nations: Case Studies of the United States, Soviet Union, United Kingdom, France, Japan, and Sweden*, ed. Theodore Dixon Long and Christopher Wright (New York: Praeger, 1975), 62-109.

¹⁵⁸ Meredith Veldman, *Fantasy, the Bomb, and the Greening of Britain: Romantic Protest, 1945-1980* (Cambridge: Cambridge University Press, 1994).

¹⁵⁹ For a different view see Edgerton, "The 'White Heat' Revisited."

Responsibility in Science. Their key concerns were the abuse of biology (for example in IQ testing), industrial hazards, environmental degradation, and state use of new repressive technologies.¹⁶⁰ Both generations of Marxist scientists and scholars contributed considerably to the social study of British science, not least its history, from Bernal to Robert M. Young and beyond.¹⁶¹

The scientific right is much less studied, though it is clear that anti-technocratic conservation movements were established between the wars, partly to protect the countryside from pylons and creeping suburbia.¹⁶² A liberal critique of planned science was developed from the late 30s, and was associated with post-war opposition to “state

¹⁶⁰ Carol Ackroyd *et al.*, *The Technology of Political Control*, (Harmondsworth: Penguin, 1977); Hilary Rose and Steven Rose, eds., *The Radicalisation of Science* (London: Macmillan, 1976); David Albury and Joseph Schwartz, *Partial Progress: The Politics of Science and Technology* (London: Pluto, 1982); Edward Yoxen, *The Gene Business: Who Should Control Biotechnology?* (London: Free Association, 1983). On the new movement and its context see: Hilary Rose and Steven Rose, “The Radicalisation of Science,” *Socialist Register*, (1972), 105-32, and “Radical Science and its Enemies,” *Socialist Register*, (1979), 317-35.

¹⁶¹ Gary Werskey, “The Marxist Critique of Capitalist Science: A History in Three Movements?,” *Science as Culture*, 16 (2007), 397-461.

¹⁶² Among the exceptions are Bill Luckin, *Questions of Power* (Manchester: Manchester University Press, 1990); Edgerton, *England and the Aeroplane*; Patrick Wright, *The Village that Died for England: The Strange Case of Tyneham* (London: Cape, 1995); Patrick Wright, *Tank: The Progress of a Monstrous War Machine* (London: Faber, 2000); Lawrence and Mayer, eds. *Regenerating England*; Patrick Zander, “(Right) Wings over Everest: High Adventure, High Technology and High Nationalism on the Roof of the World, 1932–1934,” *Twentieth Century British History*, 21 (2010), 300-29.

medicine.” Its ablest ideologue was the Hungarian émigré Michael Polanyi, Professor of Physical Chemistry and then of Social Philosophy at Manchester, and closely associated with classically liberal philosophers and economists such as Friedrich von Hayek. They were profoundly hostile not only to Marxism but also to centrist scientism, and their writings were well supported by the CIA.¹⁶³ Yet there were also powerful technocratic traditions on the right that helped drive nationalistic scientific and technological policies, and certainly the great military-technological effort.¹⁶⁴

From the late 1960s then, post-war technocratic nationalism came under attack from both wings of politics: from the Left who were antimilitarist, environmentalist, and sceptical of pharmaceuticals; and from the neo-liberal economists of the Right who attacked state technology, though only the civil version.¹⁶⁵ The 1970s saw increased scepticism about

¹⁶³ On Polanyi, see McGucken, *Scientists, Society and State*; Frances Stonor Saunders, *Who Paid the Piper?: the CIA and the Cultural Cold War* (London: Granta, 1999); John Jewkes et al., *The Sources of Invention* (London: Macmillan, 1958).

¹⁶⁴ Edgerton, *England and the Aeroplane*; Edgerton, *Warfare State*; S. Waqar H. Zaidi, “The Janus-Face of Techno-Nationalism: Barnes Wallis and the ‘Strength of England’,” *Technology and Culture*, 49 (2008), 62-88.

¹⁶⁵ John Jewkes, “Government and High Technology,” *Institute of Economic Affairs Occasional Paper*, no. 37 (1972); David Henderson, “Two British Errors: their Probable Size and Some Possible Lessons,” *Oxford Economic Papers*, 29 (1977), 186-94; Duncan Burn, *Nuclear Power and the Energy Crisis: Politics and the Atomic Industry* (London: Macmillan for the Trade Policy Research Centre, 1978). It is also worth noting the importance of economists in British environmentalism – for example Barbara War, E. F. Schumacher, and E. J. Mishan.

large-scale civilian programs, like the Advanced Gas Cooled Reactor and the Concorde, and modernisation through science and technology increasingly lost its appeal to younger generations of intellectuals, influenced by ecological concerns and a more culturally oriented New Left. As we note below, these attacks did not bring the end of such programs, but the old triumphalism was gone. And it was the neo-liberal right, rather than the libertarian left that won out ideologically. Indeed by the 1980s, Britain, with the United States, was at the center of a general ideological, political, and economic shift to the right, strengthened by a new economic globalization and victory in the Cold War.

For many politicians around the world, Thatcherism as well as Reaganomics became models for new relations among governments, industry, and public services. Though she was the first scientist prime minister (with a chemistry degree from Oxford), Margaret Thatcher was deeply sceptical of “social engineering” and of the professions, including medicine. Her denationalisation of industry – a mixture of privatization and liberalization – went along with a further denationalization of research. Her advisors were hostile to the planning of science, yet paradoxically the Thatcher years saw a radical centralisation of control over the universities, and a strengthening of central control of state-funded research. The aim was to cut expenditure and to change culture,¹⁶⁶ and in this she succeeded. The old certainties of public service and state-led development gave way to a cult of entrepreneurs, managers, and management-consultants, which continued to operate in the early twenty-first century in the public sector as well as the private. State funding

¹⁶⁶ D. E. H. Edgerton and K. S. Hughes, “The Poverty of Science: A Critical Analysis of Scientific and Industrial Policy under Mrs Thatcher,” *Public Administration*, 67 (Winter 1989), 419-33.

for university research remained vital, and the popularity of the NHS protected it from major moves towards private insurance, but cumbersome external assessment mechanisms were imposed on universities and “internal markets” introduced to the NHS. Large-scale philanthropy, especially the cancer charities and the Wellcome Trust, emerged as a major determinant of medical research. The academic scientific community remained generally centrist in its politics and committed to increasing state funding. Indeed in the mid-1980s, faced with funding cuts, a scientists’ organisation called “Save British Science” renewed the claim that Britain had long been hostile to science and technology.¹⁶⁷ Thatcherite scientists were rare – an exceptional neo-liberal account of science met with howls of rage.¹⁶⁸ The scientific élite became increasingly concerned with propaganda for science – by the end of the century Britain had invested in “science-centres” aimed at children and the bookshops were full of popular science books.

De-nationalization and Internationalization

In a modernising nation, the state was expected to take an increasing role in leading and controlling research and the applications of science and technology – a scientific revolution and state planning were felt to go hand in hand. But slowly, and at first secretly, the viability of *national* programs had come to be questioned. In 1958 Britain stopped independent development of nuclear weapons and nuclear reactors for submarines – it

¹⁶⁷ Pavitt, *Technical Innovation*; Barnett, *Audit of War*; Edgerton, “The Prophet Militant and Industrial,” and “Decline of Declinism.”

¹⁶⁸ Terence Kealey, *The Economic Laws of Scientific Research* (London: Macmillan, 1996).

depended on the United States, as it also did for long-range missiles. In the early 1960s, congruent with an early attempt to join the European common market, two large civilian trans-national projects were started – the Concorde supersonic airliner (with France) and the development of a satellite launcher (through a consortium of European nations). They were followed in the mid-1960s and beyond by Anglo-French and European military projects. In “pure” science too, European organisations played important roles – for example the European Organization for Nuclear Research (CERN) and the European Molecular Biology Organization (EMBO).¹⁶⁹ And by the end of the 1960s it was understood that expenditures on research and development, even for civil projects, did *not* correlate positively with economic growth.¹⁷⁰

Nonetheless, in some new fields, for example electronics and computing, new national programs were developed in the 1970s, and in agriculture the strong state subsidy of private industry, supported by state and private research, continued to transform productivity. Even in defence, R&D rose in absolute terms in the 1970s and the early 1980s; as a new Cold War took root, the state’s R&D program was remilitarised. But with the ending of large-scale civil development programs, the fall in defence R&D from the mid-1980s, and the liberalization and privatization of government research under Margaret Thatcher, expenditure by government on R&D fell from 0.9 percent to 0.5 percent of GDP by the end of the 1990s. The proportion of GDP devoted to R&D peaked at around 2.3 percent

¹⁶⁹ See John Krige and Dominic Pestre, eds., *Science in the Twentieth Century* (Amsterdam: Harwood Academic, 1997).

¹⁷⁰ Edgerton, “The ‘White Heat’ Revisited.”

in the early 1960s; in the 1980s and 1990s it drifted downward, to 1.8 percent in 1999 -- levels not seen since the 1950s.

Since the 1980s, the previously assumed relations between national capacity in R&D, national-champion industrial firms, and national economic development shaped by state action have weakened considerably, not least through the continued decline of manufacturing industry. In Britain, more than in most of Europe, privatization, marketization, liberalization, internationalization, and globalization have substantially modified the structures and processes of science, technology, and medicine, though the state continues to fund most university work and the vast majority of health care. In 1984 the Anglo-Dutch firm Unilever bought the Plant Breeding Institute and the National Seed Development Organisation from the government; in 1998, they were sold on to the U.S. firm Monsanto. The former National Research Development Corporation, set up in 1948 to exploit public sector research was privatised in 1992. The atomic weapons establishment, part of the Ministry of Defence, was transferred to a private contractor in 1993. Large-scale development of British nuclear reactors was run down, and American designs imported. Privatization of electricity supply further reduced the civil nuclear program, which was itself privatised in the mid-1990s. The National Physical Laboratory – that great symbol of state civil science – was “contractorised” in 1995, and in 2001 all the military laboratories, with the exception of the nuclear program and the biological and chemical warfare center at Porton Down were transferred to a new entity called QinetiQ plc, which was intended for the private sector. Many of the national industrial projects of

the 1960s and 1970s were later left to the international market.¹⁷¹ Generally, the British subsidiaries of foreign multi-nationals performed higher proportions of research, and increasing proportions of the industrial research expenditure came from abroad.¹⁷²

By the end of the 1990s the declinist emphasis on the poverty of British science gave way among elite scientists to an emphasis on the strength of British academic science in comparative terms. This new argument for support, congruent with the emergent anti-declinist accounts, had much evidence in its favor.¹⁷³ The MRC remained a major supporter of world-class biomedical research, especially in molecular biology, but other agencies became increasingly important.¹⁷⁴ The Wellcome Trust cut its links with the parent pharmaceutical company and became a major funder of medical research, alongside the cancer charities. Around 2000, it collaborated with government in a widespread renovation of university science facilities. The drug industry saw a series of mergers, and some internationalisation of research, but remained competitive. For medical technology, where Britain was notable for inventions in the 50s and 60s (for example, the CT scanner

¹⁷¹ Campbell-Kelly, *ICL*; Mick McLean and Thomas Rowland, *The Inmos Saga: A Triumph of National Enterprise* (London: Pinter, 1985).

¹⁷² David Edgerton, "Research, Development and Competitiveness," in *The Future of UK Industrial Competitiveness and the Role of Industrial Policy*, ed. K. Hughes (London: Policy Studies Institute, 1994).

¹⁷³ Robert M. May, "The Scientific Wealth of Nations," *Science*, 275 (7 February 1997), 793-6. Robert May was then the Chief Scientific Advisor to the British government. His arguments echoed those of Terence Kealey.

¹⁷⁴ Miguel García-Sancho, *Biology, Computing, and the History of Molecular Sequencing: From Proteins to DNA, 1945-2000* (London: Palgrave Macmillan, 2012).

developed by EMI and the artificial hip developed by a surgeon, John Charnley), British companies tended to be overtaken by American rivals, which were faster to innovate and familiar with their larger and richer markets.¹⁷⁵

In Britain around 2000, the biomedical sciences seemed increasingly central to economic policy as well as health. Whether they achieved any significant economic impact is another matter.¹⁷⁶ In universities, they easily rivalled the physical sciences, which had long dominated the science faculties. But they were also controversial; Britain was known worldwide for the epidemic of mad cow disease in the last years of the Conservative government, and New Labour was rocked in 2001 by a major outbreak of Foot and Mouth Disease. Both helped build a public suspicion, which is also evident in British debates over vaccination, genetically modified organisms, and the retention of bodily organs in hospitals.¹⁷⁷ Large increases in funds for medicine, not least through charities, have

¹⁷⁵ See for example, J. S. Metcalfe and John V. Pickstone, "Replacing Hips and Lenses: Surgery, Industry and Innovation in Post-War Britain," in *Innovative Health Technologies: New Perspectives, Challenge and Change*, ed. Andrew Webster (Basingstoke: Palgrave Macmillan, 2006); Bettyann Holtzmann Kevles, "The Physical Sciences and the Physician's Eye. Dissolving Disciplinary Boundaries," in *The Cambridge History of Science, vol. 5: The Modern Physical Sciences*, ed. Mary Joe Nye (Cambridge, Cambridge University Press, 2003), pp. 615-33.

¹⁷⁶ Geoffrey Owen and Michael M. Hopkins, *Science, the State and the City: Britain's Struggle to Succeed in Biotechnology* (Oxford: Oxford University Press, 2016).

¹⁷⁷ Abigail Woods, *A Manufactured Plague. The History of Foot and Mouth Disease in Britain* (London: Earthscan, 2004); for attitudes to tissues see Duncan Wilson, "'Make Dry Bones Live': The Public Perception of Tissue Culture in Britain, 1918-2004" (PhD thesis, University of Manchester, 2005).

accompanied continued public scepticism and a loss of authority by medical professionals. Doctors and the new ranks of managers and health economists have pushed for “evidence-based medicine,” but in an increasingly litigious and consumerist context. In medicine, the concerns are usually raised by the patients’ groups that have proliferated since the 1970s; for environmental issues the chief propagandists are international charities such as Greenpeace or Friends of the Earth.

In the early twenty-first century, public discussions about science in Britain have been less about national economic growth or defence, and more about the possibilities and threats of informatics and molecular medicine. The politics of science have become increasingly public and international; but no longer, if ever, could one easily line up science versus anti-science, though this is how the science lobby sometimes portrays its problems. Increasingly, we would argue, science must be understood as multiplex, and projects examined for the *different* values they incorporate. The critique of science can then be much more than a demand for more (or less); it could be about choices between projects and between different kinds of science-politics, about the *development* of science, about on-going history.

As we have tried to show, the older historiographies of British science often relied uncritically on arguments made by researchers to demand more funds. Those arguments were often about industry and military might. But much of the industry and the might have now departed, and newer debates are concerned more with effects of science than with levels of investment. In the early twenty-first century, most of Britain’s opinion-formers

have barely known the Empire, or ever felt Britain to be a Great Power. They grew up in a world when economic status was insecure, and they learned to see a world where economic success has been spread among many nations, east and west. As globalization and economic communities have weakened the nation-state, as the priorities of medicine have been debated and those of economic development have come under environmentalist scrutiny, we will need more varied and more international histories. In these international histories, Britain will have a major place; for over the span of this chapter – from the global Empire to its end, and across a wide range of political and institutional regimes – Britain has remained among the most creative of scientific nations.